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MEASUREMENT OF THE PROPERTIES OF BROKEN ICE ZONES AND ICE RUBBLE

MAY 1988

Preparation Agency:
K.R. Croasdale and Associates

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and Development (PERD)
Marine Product Line, Headquarters
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17. Abstract

This report describes the results of a project to measure the properties of ice rubble and broken ice. The purpose was to examine the refreezing of ice rubble and obtain measurements for comparison with analytical models. A time-dependent bearing settlement test on grounded ice rubble was also performed to obtain large-scale data.

Measurements were taken at a grounded rubble field around an artificial island in the Arctic and, in an outdoor basin in Calgary. The results were compared with the predictions from analytical models.

Measurements taken in the ice basin agreed more consistently with predicted levels than those taken in the Arctic. The report offers a number of possible explanations for the anomalies. Since the bearing-settlement test was conducted only on warm ice rubble, the report recommends that the analytical model should be tested against measurements on colder ice rubble.

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17. Résumé

Le présent rapport décrit les résultats d'un projet de mesure des propriétés des fragments de glace et de la glace fragmentée. Il s'agissait d'étudier le regel de fragments de glace et d'obtenir des mesures permettant la comparaison avec des modèles analytiques. Un essai de tassement en durée déterminée sur des fragments de glace échouée a été réalisé pour obtenir des données à grande échelle.

Des mesures ont été prises sur un dépôt de fragments échoués autour d'une île artificielle dans l'Artique ainsi que dans un bassin de glaces à ciel ouvert à Calgary. Les résultats obtenus ont été comparés aux prédictions des modèles analytiques.

Les mesures prises au bassin de glaces ont concordé de façon plus régulière avec les prédictions que celles prises dans l'Arctique. Le rapport présente un certain nombre d'explications possibles à l'égard des anomalies. Étant donné que l'essai de tassement n'a été réalisé que sur des fragments de glace tiède, le rapport recommande que le modèle analytique soit éprouvé de nouveau avec des mesures prises sur des fragments de glace plus froide.

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PREFACE

This report is one of several reports on the research work in the field of marine engineering, identified and managed by the Marine Product Line and Technology Resources groups of Public Works Canada, with funds provided by the Interdepartmental Panel on Energy Research and Development (PERD)

PERD was established in 1974 to coordinate research on energy by the Federal Government with objectives to provide, in conjunction with efforts in the private sector and the provinces, the technical basis for:

- maintaining oil self-sufficiency over the short term, in view of dwindling conventional supplies;

- developing a diversified energy economy, less dependant on oil and gas in the mid-term; and

- making Canadians less reliant on non-renewable energy sources in the long term.

The research work undertaken by Public Works Canada in Marine Engineering with funds from PERD has been directed particularly toward the following two main topics:

1. Ice/Structure Interaction
2. Construction and Towing of Reinforced Concrete Caissons in the Arctic.

This report is being published with a view to enhancing the technology in the field of Marine Engineering and contributing toward the objectives of PERD.

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1.0 Introduction, Background and Justification

Broken ice zones and ice rubble areas are very common in the offshore northern environment. Grounded ice rubble fields often occur around offshore structures, and broken ice in the form of first-year pressure ridges occurs frequently, even in the nearshore zones.

For offshore operators the most important properties of broken ice zones are those governing bearing capacity and lateral load transfer through grounded ice rubble. A better understanding of bearing capacity could lead to operating efficiencies in:

- construction operations (conducted from the ice),
- the use of grounded ice rubble (possibly combined with spray ice) as an exploratory drilling pad (or relief-drill pad),
- pipelaying operations from the ice, and
- winter roads.

A better understanding of lateral load transfer through ice rubble could lead to efficiencies in:

- artificial island and offshore structure design, and
- the use of grounded ice rubble (possibly combined with spray ice) as a protective barrier for cost-effective offshore drilling, construction, production, etc.

Until recently, the available analytical models (at least in the public domain) to predict the behaviour of broken ice zones were quite simplistic. They were not reliable enough to allow optimization of the previously mentioned operational issues. New analytical models are under development, but it is envisaged that precise field and experimental data will be necessary to calibrate and prove them.

The overall logic and analytical models for broken ice zones are shown in Figure 1. In a recently awarded study from Public Works Canada, (reference 1), K. R. Croasdale and Associates participated in developing analytical models for:

. Thermal consolidation and mechanical properties

. Bearing Capacity

. Lateral resistance

Obviously the first model is extremely important because its output will significantly influence the other two. Furthermore, comparison with precise field measurements will be vital to ensure that the model is correct, especially in terms of predicting with time the depths of the various layers as depicted in Figure 2. In addition, temperature profiles, initial porosities, salinities, etc. are important parameters which will ultimately affect mechanical properties.

In reviewing field and experimental work which has been conducted to date on rubble fields and pressure ridges, it was concluded that the available data, although better than nothing, was insufficient in detail to properly calibrate the more precise analytical models being developed. Certainly, consolidation thicknesses had been measured, but often only at one time late in the winter season. Rates of consolidation had been inferred from thermistor strings, but not confirmed in the early season by drilling. Moreover, in all cases, the initial state of the rubble in terms of porosity, salinity, etc., had usually not been measured. Finally, precise site-specific meteorological data (including air temperature, wind speeds, radiation, etc.) had usually not been gathered. The above deficiencies are not surprising because most studies of ice rubble (or ridges) had been specific to a limited time period, and/or had often been part of a larger study having a variety of objectives.

This project was proposed as a narrowly focused study to primarily address the thermal consolidation of ice rubble with time during the winter; the intent being to measure the thermal consolidation of ice rubble, as well as the relevant ice parameters and the meteorological conditions; and then to compare these measurements with those calculated using the analytical models developed in reference 1.

It was also possible during this project to measure the time-dependent bearing settlement of grounded ice rubble. These measurements are also compared with the analytical models developed in reference 1.

2.0 Summary

A research project was conducted to measure the properties of ice rubble and broken ice. The study focused on the refreezing of ice rubble after its formation. A time-dependent bearing settlement test on grounded ice rubble was also performed.

Measurements were conducted in the Arctic at a grounded rubble field around an artificial island, and also in a large outdoor ice basin in Calgary. The measurements were compared with the results from analytical models.

Measurements in the ice basin were in good agreement with the analytical models. Measurements in the Arctic were less easily performed and the results did not consistently agree with the analytical model for the refreezing of ice rubble. Explanations for the lack of consistent agreement are offered.

3.0 Research Objectives

- The primary objective of this project was to conduct measurements on the freezeback of ice rubble, gather all relevant ancillary data, and compare the measurements with theory.

- The secondary objective of this project was to measure the time-dependent bearing settlement of grounded ice rubble and compare the results with theory.

4.0 Overall Scope of Research Work

It was originally intended to conduct all of the measurements for this study in the Arctic at an artificial island surrounded by a stable ice rubble field. The original plan called for four field trips to the Arctic commencing in November as soon as the ice rubble had formed.

The intent was to focus on a relatively small area of the rubble field, and to conduct initial measurements and install equipment as soon as the rubble had formed.

The initial measurements were to have been:

- rubble geometry (sail and keel),
- degree of grounding,
- ice temperatures,
- water temperatures,
- ice and water salinities,
- initial porosities,
- block sizes, and
- ice types.

Instruments to be installed and left at site were to have been thermistor strings and a weather station.

The locations for both the thermistors and subsequent augering (and porosity measurements) were to have included locations with different sail heights, and possibly both grounded and ungrounded zones.

The data acquisition system was planned to operate remotely and record daily ice temperature profiles and the meteorological conditions (including air temperatures, wind and solar radiation). About once a month during the winter, during short site visits, the thickness of the consolidated zone would be measured by augering. Also, measurements of the porosity in the unconsolidated zones would be made. Each month as data was collected it would be reduced and analyzed.

During analysis of the data, the measurements were to be compared with predictions based on the analytical model.

At the time of the original proposal, Esso Resources Canada had agreed to allow the work defined above to be conducted around one of their islands. Unfortunately, Esso's drilling plans were upset by the late summer storm at Minuk. The island was seriously eroded and the drilling rig was damaged and had to be replaced. The new camp at Minuk had fewer beds, and Esso concluded that they could not accommodate research personnel during the early part of the winter, but only later during February and March. On the other hand they agreed to allow their ice test basin in Calgary to be used for ice rubble consolidation and bearing load tests.

Consequently, the planned scope of the project was changed to be in two parts:

(1) Experiments in the ice basin.
(2) Measurements on the ice rubble around the Minuk island during February and March, 1986.

In the ice basin, ice rubble was to have been created (beginning in January) by pulling ice sheets into the back wall. It was envisaged that the ice sheets would be in the 10 cm to 15 cm thickness range. After each pull, the rate of thermal consolidation, together with other influencing parameters were to be measured to compare with those predicted by the analytical models. Temperature profiles were also to be recorded.

With repeated pulls, it was expected to be able to form a large grounded rubble field in the deep end of the basin. In late February, a loading box was to be placed on the rubble, vertical loads applied by filling the box with sand bags, and the vertical response of the rubble recorded.

The arctic field measurements were to be conducted during two field trips, one in February and one in March. During this part of the study, measurements of the consolidation thicknesses in a rubble field around an arctic structure were to be made. Influencing parameters such as porosity,

sail geometries, snow cover, block sizes, temperatures and salinities, etc., were to be measured. Meteorological records either from the island or Tuktoyaktuk were to be assembled, as well as aerial photos of the ice rubble at various times during the winter. Actual consolidation thicknesses would then be compared with those predicted by the analytical model.

The specific details of the work conducted varied slightly from the planned scope described above. Details of the actual work performed are described in the following sections of this report.

5.0 The Ice Basin Tests for Thermal Consolidation

5.1 Description of the Ice Basin

The Esso ice basin is a large outdoor facility which was constructed in 1973 to perform large scale model tests on ice-structure interaction. The basin is about 50 m long and 30 m wide. The water depth is about 3 m at the deep end, and 1.4 m at the shallow end (see Figure 3).

Throughout the winter, a number of ice sheets are naturally grown and can be moved against the structure by means of a pulling system built into the facility. The spent ice sheet is removed by dispelling it over the back weir during a test or by scooping the broken ice blocks out of the basin with an overhead crane. Once a test has been completed, the drive system is reversed and a new ice sheet is allowed to grow. The drive system has a maximum pulling capacity of about 100 tons. Drive units on either side of the basin are powered by a 150 kW electric motor driving through a hydraulic pump and motor onto a geared speed reduction in the order of 1000:1. The maximum ice speed that can be produced against a structure is about 0.25 m/s.

The ice can be fresh or saline. During, a normal winter ice up to about 0.8 m thick can be grown as a single ice sheet, or about 10 ice sheets in the range of 10 to 15 cm can be tested. The ice surrounding the towing boom at the shallow end of the basin is retained intact during each test. This ensures that the towing boom is well frozen into thicker ice.

5.2 Experimental Plan

For this project there was no test structure mounted in the deep end of the basin. It was envisaged that by lowering the water level slightly, the ice sheet could be induced to fail against the back wall of the basin and create ice rubble. By moving back the towing system after each pull a new thin ice sheet could be grown. By repeated pulls of ice about 10 to 15 cm thick it was expected that ice rubble about 9 m wide could be created (see Figure 4). Loads to create the ice rubble were estimated

using measurements from previous ice rubble tests in the basin (Graham et al, reference 2). For a fresh water ice sheet 10 cm thick an average load of 30 tons (peak of 60) was predicted.

As each strip of rubble was formed the plan was to conduct the following observations.

(1) Photograph the ice rubble.

(2) Measure the freezeback rate in the ice rubble (using an auger and a measuring stick).

(2a) Measure the temperature of the refrozen zone - at the surface and mid-thickness.

(3) Measure piece sizes.

(4) Estimate porosity of rubble.

(5) Estimate the thickness of the ice rubble if not grounded.

From the start of the experiment to the end, the following data was to be obtained.

(1) Continuous recording of wind and temperature.

(2) Daily ice thickness measurements.
- Refrozen thickness in rubbled zones
- Thickness of surrounding sheet ice

(3) Daily ice temperature measurements.

(4) Daily snow thickness measurements.

(5) Water temperatures (below ice).

The experimental plan described above was modified by events. Some difficulty was experienced in creating the ice rubble as envisaged. The basin towing system is now 12 years old and repeated failures of the drive chain occurred. Some ice rubble was eventually formed in the method planned, by using two large towing trucks to pull the ice sheet. But their towing capability was limited and the ice had to be pre-broken using a crane and a wrecker's ball. It was also found that the rubble tended to cause bending failure of the thick sheet as it was pushed into the rubble pile.

It was decided therefore to use a different approach to create the grounded ice rubble. By breaking the ice with the crane and using a scoop, it was possible to pile up broken ice until it grounded (see Figures 5 to 7 for photographs of this operation). To retain the broken ice, a 10 m x 10 m wire cage was built from chain link fencing (see Figure 8).

In this manner, grounded ice rubble was created on January 30 and measurements of freezeback continued through February.

5.3 Results of Freezeback Measurements

Every day during the measurement period, the ice rubble was augered to estimate freezeback. Measurements were taken within the area of the rubble, and also in the surrounding ice sheet (for reference).

Porosities and freezeback within the rubble were estimated by augering at three general locations labelled the middle area, the north area, and the south area (see Figure 9). Ice surface temperatures and water temperatures were also measured.

On four days between February 15 and February 20, temperature profiles within the refrozen layer were obtained (see Figure 10).

A compilation of the results of the freezeback thicknesses, and ice surface temperatures is given in Table 5.1. Values of porosities for the first few days, estimated by augering are given in Table 5.2. Note that

for the purpose of this study, porosity is defined as the total length of voids (along an augered hole) divided by the total length of the hole.

Figure 11 shows the freezeback in the ice rubble plotted against time. Because block sizes were approximately 0.3 m thick, it can be appreciated that depending on the exact location of the thickness measurement, an apparent sudden increase or decrease could be due to the auger either penetrating or not penetrating an ice block, or penetrating an ice block oriented at a different angle from the previous measurement. However, care was taken, especially during the early period of the measurements to avoid the surface ice blocks. Also shown in Figure 11 is growth of the surrounding sheet ice with time.

5.4 Ancillary Information

During the test period, wind and temperature data were continuously recorded at the ice basin. These measurements were reduced to daily averages and are shown in Table 5.3.

The weather conditions for Calgary during February were also obtained from Environment Canada (Table 5.4). The readings obtained at the ice basin agree quite well with those from the weather office.

5.5 Discussion of Results

Comparison of the measured results with theory will be made later in Section 8.0. A scan of the measurements indicates expected trends. For example, the rate of refreezing within the ice rubble is higher than the surrounding sheet ice growth (see Figure 11). When a snowfall occurred about day 16 there was a slowing down of the ice growth rate. (Note, that after three days the snow was removed to enhance the rate of growth). After day 24 when above-freezing temperatures and strong sunlight prevailed, the ice thickness in both the ice rubble and the sheet ice started to reduce. As expected, ice surface temperatures were always higher than the air temperatures. The temperature profiles through the consolidated layer showed an approximate linear trend, but with some trace of transient response to significant changes in air temperature.

In general, the measured results appear to be plausible.

TABLE 5.1

REFREEZE MEASUREMENTS - ICE BASIN

DAY	REFREEZE THICKNESS OF RUBBLE (cm)	ICE SHEET THICKNESS OUTSIDE OF RUBBLE (cm)	SNOW COVER (cm)	TEMPERATURE OF ICE SURFACE (oC)	TEMPERATURE OF WATER (oC)
JAN 31	1.50	1.5		0	0.2
FEB 1	3.10	3.1		-1.5	0
2	4.00	4		-0.8	0.3
3	8.00	4.5		-2	0
4	9.00	5.5		-4	0
5	12.00	7		-5	0
6	15.00	8.5		-5	0
7	27.00	15		-5	0
8	29.40	15		-7	0
9	36.00	17.5		-4	0
10	32.00	18		-5	0
11	34.00	19		-2.5	0
12	36.00	18		-5	0
13	37.00	22		-10	0
14	43.00	21.5		-8	0
15	36.00	30.20	5.08	-9	0
16	36.00		10.16	-9	0
17	42.00	26.00	10.16	-12	0
18	44.00	27		-17	0
19	45.00	35		-20	0
20	57.00	36		-14	0.5
21					
22					
23					
24	62.00	23		-4	0.5
25	59.00	20		0	0
26	48.00	19		2	1
27	36.00	17.5		0	1
28	32.00	16		2	1
MAR 1					
2					
3	29.00			0	1

Table 5.2

POROSITY MEASUREMENTS - ICE BASIN

DAY	THICKNESS OF VOIDS (NORTH) (cm)	THICKNESS OF VOIDS (MIDDLE) (cm)	THICKNESS OF VOIDS (SOUTH) (cm)	RUBBLE THICKNESS (NORTH) (cm)	RUBBLE THICKNESS (MIDDLE) (cm)	RUBBLE THICKNESS (SOUTH) (cm)	POROSITY (NORTH)	POROSITY (MIDDLE)	POROSITY (SOUTH)
JAN 31	43		79	246		246	0.18		0.32
FEB 1	86	23	58	246	272	246	0.35	0.08	0.24
2	58	79	79	246	272	246	0.24	0.29	0.32
3	127	101	36	246	196	221	0.52	0.52	0.16
4	65	46	137	246	221	221	0.27	0.21	0.62
5	74	56	58	208	246	208	0.36	0.23	0.28
6	69	39	64	198	234	198	0.35	0.16	0.32

NOTE:

POROSITY IS DEFINED AS VOID THICKNESS DIVIDED BY TOTAL RUBBLE THICKNESS

TABLE 5.3

DAILY BASIN WIND VELOCITY AND TEMPERATURE

DAY	WIND VELOCITY (km/hr)	TEMP. (deg. C)
JAN 30	7.33	7.33
31	3.17	2.00
FEB 1	3.66	-0.83
2	7.16	-3.17
3	7.83	-0.58
4	4.33	-3.98
5	22.00	-5.88
6	10.83	-10.48
7	8.93	-8.38
8	6.61	-10.88
9	9.00	-9.28
10	6.83	-12.18
11	5.33	-9.18
12	11.67	-10.88
13	10.50	-16.33
14	10.00	-11.42
15	13.33	-13.50
16	13.00	-28.00
17	8.50	-28.17
18	5.50	-32.67
19	7.33	-34.17
20	9.17	-20.33
21	13.00	-19.50
22	6.50	-12.00
23	8.17	-2.50
24	10.00	3.17
25	25.50	11.25
26	14.50	9.17
27	6.17	6.50
28	13.83	12.17
MAR 1	10.83	8.00
2	8.17	9.17
3	8.67	8.00
4	20.17	10.50
5	14.17	5.17
6	16.17	-8.50
7	8.33	-5.17
8	11.67	0.83
9	7.17	2.50
10	8.17	3.33
11	6.00	2.17

TABLE 5.4

Environment Canada / Environnement Canada
Atmospheric Environment Service / Service de l'environnement atmosphérique

MONTHLY METEOROLOGICAL SUMMARY
SOMMAIRE MÉTÉOROLOGIQUE MENSUEL

MONTH/MOIS: FEBRUARY / FEVRIER 19 86

AT/À: CALGARY (A) ALBERTA

LAT: 51 • 06 'N LONG: 114 • 01 'W ELEVATION: ALTITUDE: 1079 METRES (ASL) MÈTRES (NMM) STANDARD TIME USED: HEURE NORMALE UTILISÉE: MOUNTAIN

DATE	TEMPERATURE TEMPÉRATURE			DEGREE-DAYS DEGRÉS-JOURS		REL. HUMIDITY HUMIDITÉ REL.		THUNDERSTORM GRADE	PRECIPITATION PRÉCIPITATIONS			SNOW ON GROUND NEIGE AU SOL	WIND VENT			BRIGHT SUNSHINE INSOLATION EFFECTIVE
	MAXIMUM MAXIMALE	MINIMUM MINIMALE	MEAN MOYENNE	HEATING DE CHAUFFE	GROWING DE CROISSANCE	MAXIMUM MAXIMALE	MINIMUM MINIMALE		RAINFALL PLUIE (HAUTEUR)	SNOWFALL NEIGE (HAUTEUR)	TOTAL PRECIP. PRÉCIP. TOTALE		AVERAGE SPEED VITESSE MOYENNE	PREVAILING DIRECTION DOMINANTE	MAXIMUM SPEED AND DIRECTION VITESSE MAXIMALE ET DIRECTION	
	°C	°C	°C	BASE 18.0°C	BASE 5.0°C	%	%		mm	cm	mm	cm	km/h		km/h	
1	7.1	-7.6	-0.3	18.3		75	49						6.4	S	WSW	19	3.2
2	6.5	-6.0	0.3	17.7		80	41			TR	TR		10.4	SE	W	26	8.8
3	5.0	-8.1	-1.6	19.6		68	44						2.9	NNW	E	9*	8.0
4	3.6	-10.2	-3.3	21.3		73	51						3.9	SSE	NNW	11	9.1
5	-0.3	-10.0	-5.2	23.2		79	57			0.4	TR		23.5	NNW	NNW	37	7.4
6	-5.4	-14.2	-9.8	27.8		79	67			TR	TR	TR	11.1	N	NNW	26	4.4
7	-4.5	-10.8	-7.7	25.7		79	62			0.2	TR	TR	12.3	N	NNW	24	2.0
8	-8.0	-12.3	-10.2	28.2		85	73			0.2	0.2	TR	9.1	SE	SE	15	1.0
9	-6.1	-11.1	-8.6	26.6		85	73			1.0	0.6	TR	10.7	SSE	SSE	22	0.1
10	-9.1	-13.8	-11.5	29.5		78	72			1.8	0.6	2	10.6	SSE	SE	13*	0.0
11	-5.4	-11.5	-8.5	26.5		85	73			1.6	0.4	2	3.9	N	N	13*	0.0
12	-8.4	-11.9	-10.2	28.2		79	72			1.2	0.2	3	11.9	N	N	28	2.3
13	-11.0	-19.5	-15.3	33.3		71	51			0.4	0.2	4	12.8	S	N	30	7.8
14	-5.2	-17.1	-11.2	29.2		79	51			4.0	1.2	4	10.0	NW	NE	32	1.6
15	-9.3	-21.7	-15.5	33.5		65	58			7.4	6.6	9	20.3	E	ENE	30	0.0
16	-21.3	-25.4	-23.4	41.4		63	57			1.6	1.1	14	22.9	N	N	43	0.0
17	-24.5	-32.3	-28.4	46.4		62	52			0.2	0.2	10	9.8	N	ESE	15*	4.9
18	-25.4	-37.1	-31.3	49.3		60	56			TR	TR	10	6.8	N	NNE	13*	7.3
19	-24.6	-37.5	-31.1	49.1		62	55			TR	TR	10	9.8	S/SSE	SSE	24	9.6
20	-1.8	-28.9	-15.4	33.4		63	36			TR	TR	10	15.2	S	WSW	30	6.6
21	-6.4	-21.8	-14.1	32.1		65	60			TR	TR	8	19.9	NNW	N	41	6.7
22	-3.7	-16.7	-10.2	28.2		57	48					8	8.2	N	NW	17	7.6
23	3.3	-9.9	-3.3	21.3		69	44					8	11.0	S	WSW	26	1.5
24	12.7	-4.0	4.4	13.6		60	44					6	10.4	E	WNW	48	8.2
25	13.9	3.9	8.9	9.1	3.9	57	44					TR	35.0	WSW	WSW	48	8.1
26	11.6	-0.4	5.6	12.4	0.6	60	29						20.2	W	W	32	9.8
27	11.7	-3.1	4.3	13.7		74	42						9.9	S	SSE	22*	8.9
28	17.3	3.1	10.2	7.8	5.2	70	23						18.7	W	W	33	5.3
29																	
30																	
31																	
				TOTAL	TOTAL			TOTAL	TOTAL	TOTAL	TOTAL			PREVAILING	MAXIMUM		TOTAL
MEAN MOYENNE	-3.1	-14.1	-8.6	746.4	9.7	71	53	0	0.0	20.2	11.3		12.8	N	SVL	48	140.2
NORMAL NORMALE	-1.5	-12.9	-7.3	713.6	2.1			0	0.3	19.1	15.5		15.8	W			127.9

DEGREE-DAY SUMMARY – SOMMAIRE DE DEGRÉS-JOURS

BELOW 18°C AU-DESSOUS DE 18°C	THIS YEAR ANNÉE EN COURS	PREVIOUS YEAR ANNÉE PRÉCÉDENTE	NORMAL NORMALE	ABOVE 5°C AU-DESSUS DE 5°C	THIS YEAR ANNÉE EN COURS	PREVIOUS YEAR ANNÉE PRÉCÉDENTE	NORMAL NORMALE
TOTAL FOR MONTH TOTAL DU MOIS	746.4	739.5	713.6	TOTAL FOR MONTH TOTAL DU MOIS	9.7	0	2.1
ACCUMULATED SINCE JULY 1 ACCUMULÉE DEPUIS LE 1ER JUILLET	3799.2	4019.0	3834.4	ACCUMULATED SINCE APRIL 1 ACCUMULÉE DEPUIS LE 1ER AVRIL	1369.6	1422.9	1382.4

DAYS WITH TOTAL PRECIPITATION: JOURS AVEC PRÉCIPITATIONS TOTALES: mm

0.2 OR MORE OU PLUS	1.0 OR MORE OU PLUS	2.0 OR MORE OU PLUS	10.0 OR MORE OU PLUS	50.0 OR MORE OU PLUS
10	3	1	0	0

DAYS WITH SNOWFALL: JOURS AVEC CHUTE DE NEIGE: cm

0.2 OR MORE OU PLUS	1.0 OR MORE OU PLUS	2.0 OR MORE OU PLUS	10.0 OR MORE OU PLUS	50.0 OR MORE OU PLUS
12	7	2	0	0

UDC 551.508.1 ( ) *Indicates more than one occurence of same speed but not necessarily from same direction.

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NOTE: 1st PAGE OF the "1985" ANNUAL THE TOTAL Precipitation and rainfall amounts for August should read 66.2mm , total annual rainfall 303.5 and the total precipitation for the 1985 YEAR 388.4MM.

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REV 9/1983

TABLE 5.4 cont'd

COMPARATIVE RECORDS / RELEVÉS COMPARATIFS	CALGARY (A) ALBERTA	MONTH / MOIS	FEBRUARY/ FEVRIER	19 86

Temperature/Température – °Celsius
Precipitation/Précipitation – Millimetres (mm)
Rainfall/Hauteur de pluie – Millimetres (mm)
Snowfall/Hauteur de neige – Centimetres (cm)
Wind speed/Vitesse du vent – Kilometres per hour (km/h); Miles per hour (mph)
Station pressure/Pression à la station – Kilopascals (kPa)

	THIS MONTH / CE MOIS-CI		PREVIOUS YEAR / ANNÉE PRÉCÉDENTE		NORMAL / NORMALE	RECORD FOR THE MONTH / RECORD POUR LE MOIS						YEARS OF RECORD / ANNÉES DE RELEVÉS
						HIGHEST MAXIMUM ABSOLU			LOWEST MINIMUM ABSOLU			
	VALUE / RELEVÉ	DATE	VALUE / RELEVÉ	DATE		VALUE / RELEVÉ	DAY / JOUR	YEAR / ANNÉE	VALUE / RELEVÉ	DAY / JOUR	YEAR / ANNÉE	
HIGHEST TEMPERATURE / TEMPÉRATURE LA PLUS ÉLEVÉE	17.3	28	11.9	27		18.9	12	1934				102
LOWEST TEMPERATURE / TEMPÉRATURE LA PLUS BASSE	-37.5	19	-32.2	09					-45.0	04	1893	102
MEAN MONTHLY TEMPERATURE / TEMPÉRATURE MENSUELLE MOYENNE	-8.6		-8.4		-7.3	2.0		1977	-24.4		1936	102
TOTAL MONTHLY RAINFALL / HAUTEUR TOTALE MENSUELLE DE PLUIE	0.0		TR		0.3	8.9		1928				102
TOTAL MONTHLY SNOWFALL / HAUTEUR TOTALE MENSUELLE DE NEIGE	20.2		20.7		19.1	49.3		1896	0.2		1977	102
TOTAL MONTHLY PRECIPITATION / PRÉCIPITATION TOTALE MENSUELLE	11.3		15.9		15.5	49.3		1896	0.2		1977	102
NO OF DAYS WITH MEASURABLE PRECIPITATION / NOMBRE DE JOURS AVEC PRÉCIPITATION MESURABLE	10		7		9	16		1948	1		1977	102
GREATEST RAINFALL IN ONE DAY / HAUTEUR DE PLUIE MAXIMALE EN UNE JOURNÉE			TR	24/28		6.4	26	1885				102
GREATEST SNOWFALL IN ONE DAY / HAUTEUR DE NEIGE MAXIMALE EN UNE JOURNÉE	7.4	15	6.4	28		27.7	10	1951				102
GREATEST PRECIPITATION IN ONE DAY / PRÉCIPITATION MAXIMALE EN UNE JOURNÉE	6.6	15	6.4	28		27.7	10	1951				102
MAXIMUM RAINFALL RECORDED IN: / HAUTEUR DE PLUIE MAXIMALE ENREGISTRÉE EN:												
5 MINUTES												
10 MINUTES												
15 MINUTES			OUT OF SERVICE DURING WINTER MONTHS...									
30 MINUTES												
60 MINUTES												
24 CONSECUTIVE HOURS / HEURES CONSECUTIVES												
MEAN WIND SPEED (km/h) / VITESSE MOYENNE DU VENT (km/h)	12.8		17.0		15.8	25.3		1964	9.2		1969	52
MAXIMUM SPEED (1 min.) (km/h) / VITESSE MAXIMALE (1 min.) (km/h)	NNW 48 NSW 48	24 25	NW 57	24		N 97	02	1959				39
MAXIMUM GUST SPEED (km/h) / POINTE DU VENT MAXIMALE (km/h)	WSW 85	25	N 89	05		NNW126	16	1972				39
TOTAL HOURS OF SUNSHINE / TOTAL DES HEURES INSOLATION	140.2		131.4		127.9	185.5		1924	63.0		1928	64
MEAN STATION PRESSURE (kPa) / PRESSION MOYENNE À LA STATION (kPa)	88.70		88.70		88.79	89.36		1947	88.44		1949	47
GREATEST STATION PRESSURE (kPa) / PRESSION MAXIMALE À LA STATION (kPa)	90.34	06	89.77	13		91.20	07	1949				47
LEAST STATION PRESSURE (kPa) / PRESSION MINIMALE À LA STATION (kPa)	86.95	16	87.46	19					86.06	16	1972	47

CLIMATOLOGICAL DATA FOR THE PAST TEN YEARS / DONNÉES CLIMATOLOGIQUES POUR LES DERNIÈRE ANNÉES

YEAR / ANNÉE	MAXIMUM TEMP / TEMP MAXIMALE	MINIMUM TEMP / TEMP MINIMALE	MEAN TEMP / TEMP MOYENNE	RAINFALL / HAUTEUR DE PLUIE	SNOWFALL / HAUTEUR DE NEIGE	TOTAL PRECIP / PRECIP TOTALE	MEAN WINDSPEED / VITESSE MOYENNE DES VENTS	MAXIMUM WINDSPEED / VITESSE MAXIMALE DES VENTS	HOURS SUNSHINE / HEURES INSOLATION	HEATING DEGREE DAYS / DEGRÉS-JOURS DE CHAUFFE	GROWING DEGREE DAYS / DEGRÉS-JOURS DE CROISSANCE		
1977	13.4	-8.9	2.0	TR	0.2	0.2	14.7	SVL 54	170.1	448	5.7		
1978	8.5	-33.7	-11.4	TR	18.3	10.8	11.9	W 41	139.7	822			
1979	6.5	-33.8	-16.8		11.0	7.8	15.7	W 74	118.6	973			
1980	8.7	-25.1	-6.7	TR	21.0	10.6	16.5	SVL 44	133.1	717			
1981	14.0	-27.3	-3.0	TR	10.9	8.6	18.1	NNW 56	153.2	599	7.0		
1982	11.1	-28.9	-10.9		15.0	10.4	17.5	W 78	116.4	808			
1983	15.0	-15.5	-1.7	1.1	6.0	5.6	12.5	SVL 37	108.8	551	2.6		
1984	17.4	-11.3	1.0		2.6	2.6	13.9	W 43	169.3	487	8.2		
1985	11.9	-32.2	-8.4	TR	20.7	15.9	17.0	NW 57	131.4	740			
1986	13.9	-37.5	-8.6		20.2	11.3	12.8	SVL 48	140.2	746	9.7		

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WIND SUMMARY (Kilometres per hour) 2 minute Means **MONTH** FEBRUARY / FEVRIER 19 86
SOMMAIRE DES VENTS (Kilomètres par heure) **MOIS**

Date	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Peak Gust Rafale maximum	Hour Heure
1	C	C	SSW	C	C	C	S	W	S	SSW	SSW	SW	C	S	S	SSW	SW	S	SSW	SW	S	WSW	SW	WSW		
			4				11	6	6	7	6	6		9	9	6	6	9	11	9	9	13	7	19		
2	WSW	W	W	W	NNW	NW	NW	NW	C	S	S	C	SE	SE	E	E	SE	ESE	SE	ESE	S	S	SE	C	W	0224
	17	22	24	26	17	24	11	9		7	6		6	4	9	15	13	11	11	2	7	2	6		44	
3	NNW	C	C	NNW	W	C	C	NNW	C	E	C	C	NNW	C	NNE	NNE	NNE	ENE	E	C	C	C	C	SSW		
	4			7	2			4		7			6		7	7	6	9	9					2		
4	C	NNW	C	C	C	C	C	E	C	C	C	C	SSW	SSE	C	SSE	S	SSE	SSE	SE	S	C	NNW	NW		
		7						6					6	7		9	11	9	9	6	7		11	6		
5	NW	NNW	N	NNW	NW	NW	NW	NW	NNW	NNW	NW	NNW	NNW	NNW	NNW	NNW	NNW	NNW	N	N	NNW	N	N	N	NNW	1456
	9	13	7	9	15	15	15	20	22	17	28	32	35	32	35	37	33	35	35	30	26	20	24	19	52	
6	N	NNW	NW	NNW	NNE	N	N	N	NNW	N	N	NNW	NW	NW	N	NE	SE	E	E	E	E	C	C	C		
	19	7	17	26	13	13	9	17	15	17	15	15	9	9	9	9	7	9	11	11	9					
7	SSE	S	S	WSW	SSW	SSW	NNW	NW	N	N	N	NNW	N	NNW	N	NNW	N	N	NNW	N	N	N	NNW	NNW		
	7	7	6	7	9	7	4	4	17	17	17	24	19	13	17	17	22	22	13	11	13	6	9	6		
8	NW	NNW	C	E	ESE	SE	SSE	S	SE	SE	SE	SSE	SSE	SE	SE	ESE	ESE	E	E	E	SE	SE	SE	SSE		
	7	6		6	4	6	7	7	15	11	7	9	7	9	11	13	11	11	13	11	9	13	13	13		
9	SSE	S	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	SSE	ESE	ESE	C	E	E	E	E	ESE	SSE	SE	SE		
	17	20	22	17	15	11	17	13	13	13	13	11	6	4	4		7	6	9	11	7	6	6	9		
10	SE	SE	ESE	SE	SSE	SE	SE	SE	SSE	S	S	SSE	SSE	SSE	SSE	SSE	SSE	SSE	S	S	SSE	SSE	SSE	S	S	
	11	9	11	11	11	13	13	13	11	9	11	13	7	13	11	13	11	9	11	13	9	11	7	4		
11	C	C	C	C	C	C	C	C	C	C	C	WSW	NW	NNW	N	N	NNE	NNE	NNE	NNW	NNW	N	C	N		
												4	4	11	13	11	13	9	9	7	7	2		4		
12	N	N	N	N	N	N	N	N	NNW	NNW	NNW	NNW	NNW	N	N	NNW	N	N	NNW	NNW	NW	C	N	NW		
	9	9	7	9	9	7	7	9	13	9	13	13	22	28	20	26	20	17	11	11	9		2	6		
13	NW	NNW	NNW	NNW	NNW	N	NNW	NW	C	NNW	WNW	C	E	SSE	SSE	S	S	S	S	S	S	SSW	SW	C	N	0240
	11	13	19	28	28	30	11	7		4	4		4	11	15	17	24	20	19	13	11	11	7		48	
14	W	NNW	C	S	WSW	C	ESE	NNW	NNW	NW	NW	NW	NW	NNW	NNE	NE	NNE	N	N	ESE	E	N	NNE	NE	NNE	2056
	9	4		7	7		6	6	11	7	9	15	9	6	7	19	6	11	11	6	4	30	17	32	33	
15	ENE	NE	NE	NE	E	ENE	ENE	ENE	ENE	E	E	E	E	ESE	E	ESE	E	E	E	E	E	E	E	E	NE	2315
	30	26	20	24	19	20	11	15	15	15	20	17	20	20	13	22	20	19	22	24	26	26	24	20	52	
16	ENE	ENE	NE	NE	NE	NNW	NNW	N	N	N	N	N	N	N	NNW	N	N	N	N	N	NNW	N	N	N	N	1257
	22	20	17	19	17	11	7	15	20	22	30	30	37	43	37	37	30	26	24	20	15	13	20	17	46	
17	NNW	NNW	NW	N	N	NNW	NW	NW	NNW	N	N	N	N	NE	NE	ESE	E	E	ESE	E	ESE	SE	SSE	NNW		
	11	9	11	9	9	4	6	6	7	7	9	9	9	11	13	15	9	15	15	13	13	11	6	7		
18	N	NNW	C	N	NNE	NNW	N	C	C	N	N	N	NNE	NE	ENE	ENE	ENE	ENE	E	ESE	SE	SE	SSE	N		
	7	7		11	13	6	7			6	6	7	6	6	7	13	9	7	4	7	11	11	7	4	—	
19	NNW	C	N	NNE	N	C	NNW	NNW	N	C	NE	C	C	S	SSE	S	S	S	S	SSE	SSE	SSE	SSE	SE		
	6		4	4	4		11	7	7		4			15	15	20	22	22	22	24	17	13	7	11		
20	SSE	SSE	S	S	S	S	S	S	SSW	SW	SSW	SW	SSW	SSW	SSW	SSE	S	WSW	W	SW	SW	WSW	SW	SW	W	1723
	15	11	17	22	17	17	20	20	17	7	9	7	15	9	6	9	17	30	28	20	15	15	11	11	46	
21	SW	WSW	NNW	NNW	NNW	NNW	NNW	N	NNW	N	NNW	N	N	ENE	SSE	SSE	SSE	SSE	S	S	S	S	S	S	N	0653
	13	13	32	33	30	33	30	41	26	17	11	22	13	6	7	22	22	20	20	20	13	13	9	11	56	
22	S	SSW	SW	N	C	SSE	SE	E	NW	N	N	N	NW	N	E	ESE	SSE	SSE	E	ESE	SE	S	S	SSW		
	11	11	2	2		2	4	11	17	13	11	7	7	4	9	9	9	11	11	9	4	9	6	17		
23	SSW	S	SSE	SW	S	S	WSW	SW	SW	S	S	SSW	S	S	S	S	SE	S	S	SSE	S	NNE	C	S	W	0549
	13	17	13	13	15	7	26	13	17	9	4	7	6	9	11	17	2	9	17	13	6	6		13	54	
24	WSW	NNW	W	SSW	S	SE	C	C	C	C	C	SSE	SSE	E	ENE	N	N	E	C	E	SSW	C	C	WSW	W	0039
	20	48	28	17	6	11						9	6	2	11	2	7	20		17	13			33	69	
25	SW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	SW	SW	SW	SW	SW	SW	SW	WSW	W	W	WSW	WSW	NNW	WSW	0147
	32	41	46	47	48	43	43	33	28	26	30	28	32	32	37	33	37	24	35	33	39	35	35	22	85	
26	NNE	NNW	NW	C	W	SW	W	WSW	W	W	W	W	W	WSW	W	W	W	W	WSW	WSW	WSW	W	C	NE	W	0731
	4	22	17		19	9	24	13	28	28	17	28	26	28	30	32	30	17	19	24	28	26		15	44	
27	NW	NNW	C	C	C	C	SW	S	SSW	SSW	S	S	SSE	SSE	SSE	SE	S	S	SSW	S	WSW	WSW	SSW	W		
	11	6					6	7	7	11	11	17	22	20	22	22	17	6	9	9	9	11	11	4		
28	SSW	W	SSW	NNW	NNW	W	NW	NW	NW	WSW	WSW	WSW	W	SSW	SSE	S	S	WSW	W	W	W	NW	NNW	NNW	W	1733
	6	7	7	2	6	28	17	20	24	28	26	22	11	13	26	24	17	22	20	33	22	20	24	24	50	
29																										
30																										
31																										

On indique un vent d'ouest par la lettre 'W'.

*Indicates later occurrences of same speed
*Indique des données postérieures de la même vitesse.

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6.0 The Ice Basin Tests for Time-dependent Bearing Settlement

6.1 Experimental Plan

By the end of February, the ice rubble was no longer grounded (due to melting from below). Therefore, prior to the bearing tests, grounding was re-established by piling new ice rubble onto the upper surface. Prior to this, the consolidated layer was broken up with a wrecker's ball. The general configuration for the bearing test is shown in Figure 13. The loading box was filled with sand bags to give a total vertical load of 167 kN. Survey posts were frozen into the ice rubble near to the water line close to the four corners of the loading box. The arrangement of the survey posts is shown in Figure 14. Survey posts were maintained in a frozen-in condition by applying daily small quantities of dry ice around the base of the posts. Settlement of the corners of the loading box was also monitored.

After loading the box, settlement was measured by survey, initially at a frequency of about 2 hours during the day. The settlement test started on March 7 and continued for about 9 days.

6.2 Results

Results of the bearing settlement test are shown plotted as settlement against time in Figure 14 and 15. The raw data is given in Tables 6.1 and 6.2.

6.3 Discussion of Results

The deflections of the upper surface of the ice rubble and loading box are obviously time-dependent, presumably because of creep in the ice. However, the first few hours of settlement data are not consistent. Some survey posts appeared to be rising rather than settling. This could have been a real effect of material at the sides of the loading box being extruded upwards, but was considered more likely due to the dry ice causing a frost heave effect on the survey posts. In any case the deflections were quite small and after about 5 hours the trend in deflection was one of steady settlement. There was some evidence of a slightly higher settlement rate during the day than at night. It is not clear whether this was due to a melting effect (in general temperatures during the day were above freezing), or whether it was simply the creep rate being affected by ice temperature changes in the upper surfaces of the ice rubble (one would expect the bulk of the ice rubble to be at the same temperature, day and night).

A comparison of box and rubble settlement shows good agreement (see Figure 16). As one would expect the box settlement was at a slightly higher rate.

Up to about 120 hours, the settlement rate was approximately constant, after this time the settlement rate increases suggesting the initiation of tertiary creep. In fact, a tertiary creep failure did occur at the end of the test and the loading box exhibited significant tilting.

A comparison of the observed creep rates with a time-dependent bearing capacity model for ice rubble is made in Section 8.0.

Table 6.1

RESULTS OF TIME - RATE OF SETTLEMENT SURVEY
(SETTLEMENT OF ICE RUBBLE AT WATER LEVEL)

TIME (hours)	SETTL. 1 (S.E.) (cm)	SETTL. 2 (N.E.) (cm)	SETTL. 3 (S.W.) (cm)	SETTL. 4 (N.W.) (cm)
0	0	0	0	0
1.25	0.32	0.64	0.6425	2.055
1.58	-2.536	-2.855	-0.15	2.215
1.75	-0.63	-0.472	0.01	
3.75	-0.47	0.64	1.5975	5.54875
4.33	0.16	1.4325	1.756	5.23
4.66	0.32	1.59	1.915	5.23
5	0.32	1.59	2.23	5.71
18.5	2.38	3.49	3.97	8.09
20.5	2.39	3.015	3.98	8.41
21.5	2.39	3.175	3.98	8.72
24	2.705	3.335	4.135	8.88
26	3.1775	4.2875	4.61	8.88
45	5.876	6.67	7.47	10.79
48	6.83	8.0975	9.37	10.79
50	7.78	9.37	10.01	10.95
69	9.37	10.48	11.59	13.23
72	11.04	12.46	13.42	15.55
74.5	11.99	13.26	14.22	16.34
90.5	14.61	16.83	17.15	19.52
93.5	14.29	15.88	17.15	19.68
94	14.13	15.88	16.99	20.15
97	14.61	16.35	17.94	20.15
98.5	15.24	16.99		20.15
104.5	15.4	17.62	18.42	19.84
114.5	18.73	20.8	21.92	24.12
117	19.37	21.12	22.23	23.33
119	18.89	21.43	22.55	23.33
121.5	19.53	22.07	23.34	23.49
122.5	19.69	23.34	23.51	24.92
138.5	23.65	26.83	27.95	29.52
140.5	23.66	26.99	28.59	29.36
143.5	25.25	28.42	29.86	30.31
145.5	25.56	29.21	30.49	31.43
146.5	25.88	29.53	30.81	31.75
162.5	30.49	34.93	37.48	40.32
165	30.64	35.41	37.79	40.63
167.5	31.6	36.68	39.38	41.43
169				42.54
170.5	32.07	37.67	40.33	
217.5	50.17	61.28	71.76	

Table 6.2

RESULTS OF TIME-RATE OF SETTLEMENT SURVEY
(SETTLEMENT OF BOX)

TIME (hrs)	SETTL. 1 (S.E.) (cm)	SETTL. 2 (N.E.) (cm)	SETTL. 3 (S.W.) (cm)
0	0	0	0
45	3.97	3.18	2.86
48	6.035	6.035	3.65
50	6.83	7.31	3.97
69	9.845	9.37	10.6325
,2	10.8	10.48	11.27
74.5	11.59	11.91	12.38
90.5	16.67	16.67	16.67
94	16.83	16.35	16.83
93.5			
97	17.62	16.2	17.62
98.5	18.89	17.78	17.94
104.5	19.21		18.57
114.5	23.82	24.39	23.81
117	24.45	22.39	22.7
119	24.61	23.18	23.18
121.5	25.57	23.66	24.29
122.5	25.88	23.66	24.77
138.5	31.59	28.9	31.27
140.5	31.91	29.05	31.43
143.5	34.45	31.44	32.7
145.5	35.25	32.23	33.81
146.5	35.88	32.71	34.61
162.5	42.55	39.38	42.55
165	42.71	39.53	43.82
167.5	43.98	41.28	44.61
169	44.14	41.28	45.24
170.5	45.09	42.23	47.13
217.5	66.68	66.04	85.41

7.0 The Arctic Field Measurements

7.1 General Scope

The arctic field program consisted of two periods of measurement at Esso's artificial drilling island, Minuk, in the Southern Beaufort Sea. The initial field trip was in late February, the second about one month later. Each period of measurement lasted about one week.

The major focus of the work was to measure the thickness of the refrozen layer at various places in the ice rubble. The general strategy being to obtain measurements for a variety of snow covers and sail heights at different places in the rubble field surrounding the dredged island.

During each measurement period a total of 12 locations were drilled using a 50 mm power auger.

7.2 Description of the Site

Figure 17 shows the relative location of Minuk in the Southern Beaufort Sea. This sand and gravel dredged island was used as a drilling platform in a location where there was 12 metres of water. The island consisted of an above-water working area and a sacrificial beach which included a below water berm that very gradually sloped towards the seafloor.

In the latter part of October ice began to form in the Beaufort Sea. Driven by winds and currents, this newly formed mobile ice was broken-up as it encountered the sloping berm of the artificial island. Where the berm was close to the water surface the fragmented ice became grounded on the berm. The grounded ice eventually extended outwards creating a rubble field around the island. From observations of block sizes, the initial rubble was formed from an ice sheet approximately 0.3 m thick. Subsequent rubble creation consisted of ice blocks with a thickness of about 0.7 m maximum.

By the end of February the ice rubble field around Minuk had stabilized in extent, see the aerial photo (Figure 18). The surrounding ice had become landfast so that only minor changes at the edges of the ice rubble were occurring. The approximate locations the twelve test sites are shown in Figure 19 and also marked on the aerial photo (Figure 20).

7.3 Specific Measurements

The field program at Minuk was designed to gather the following information at specific sites within the surrounding rubble field:

- snow cover thickness,
- sail height,
- refrozen layer thickness,
- temperature profile through the rubble layers,
- porosity of sail and keel, and
- salinity of the refrozen rubble.

To measure these properties, as many locations within the rubble field as time permitted were to be investigated (12). The locations were selected to represent a variation in snow cover thicknesses and sail heights. At each selected site a local and a 3 m radius average snow cover thickness was measured. In addition the density and the snow texture were recorded. Using thermistor probes and a conventional alcohol thermometer (as a backup), the ambient air and snow cover/ice rubble interface temperatures were noted at each location. A gas powered auger using 50 mm diameter auger flites was used to drill through the rubble. At depth intervals of about one metre the thermistor probe was used to measure the downhole temperature of the rubble. The porosity was measured by noting the distance dropped when encountering a void while drilling. Special attention was given to note at what depth slushy cuttings were first observed. This was assumed to indicate the approximate lower extent of the refrozen layer. To determine the sail height and the consolidated layer thickness the hole was drilled down through the keel. The subsequent stabilized water level in the hole was taken as the sea level and the sail height and refrozen layer thickness were measured relative to this. Little

information could be gathered about the keel because of the ever present problem of the auger flites becoming frozen in the hole due to the rapid refreezing of the slush and/or water. Referring to Figure 2, the field program concentrated on measurements for the first three layers of the idealized layers within a grounded rubble field. These are the most important in terms of testing the analytical model for thermal consolidation.

The first field trip was initiated on February 20, 1986. During the seven day period of the field study twelve sites on the west side of the rubble field were monitored. During the second trip, a month later, the same twelve locations were remonitored.

7.4 Results

The results of the first field trip in February are presented in Table 7.1. Benchmark values of the ice thickness and salinity were measured from the surrounding ice sheet outside the rubble field.

The second field trip to Minuk was conducted one month later in late March. At each of the previously marked locations a second hole close to the first one was drilled through the rubble. The results of the second field trip are presented in Table 7.2.

Measurements of snow cover thickness, sail height and refrozen layer thickness relative to sea level are plotted in Figures 21 and 22.

7.5 Discussion of the Results

Comparing results obtained from the initial field trip (presented in Table 7.1 and Figure 21) with those from the final field trip (Table 7.2 and Figure 22) the following observations were made:

(1) At every site with the exception of site 2 and site 3, the refrozen layer thickness increased over the period of one month. Figure 23 shows the increase in the refrozen layer thickness at each site with the exception of sites 2 and 3. Sites 2 and 3 showed a decrease in thickness, which was most likely due to scatter in thickness measurements due to the random orientation of the blocks of rubble. It is likely that the initial holes in February were drilled through blocks of rubble that were oriented in a near-vertical position. Whereas, the second holes in March, about a metre away, may have been drilled into blocks oriented horizontally.

(2) The sail heights at almost every location remained relatively the same over the course of one month. The only major exception was site 10 where the sail at this site actually decreased. This may be due to localized settlement of the rubble, which seems likely since the ice surface level at site 8, which is located at the base of the sail on which site 10 was situated, had settled over 10 cm since the first field trip and was below the water level. This indicates that the base of the sail was subject to flexural stress, possibly due to the settlement of the sail.

Further discussion of the measured values and comparison with those predicted using theory is given in Section 8.0.

DATE DRILLED	SITE	SNOW COVER CHARACTERISTICS				TEMPERATURE PROFILE												RUBBLE PROFILE			
		LOCAL THICKNESS (m)	5m RADIUS THICKNESS (m)	SNOW * TEXTURE	SNOW DENSITY (gm/cc)	AMBIENT AIR TEMP. (°C)	ICE SURFACE TEMP. (°C)	1		2		3		4		5		MAX. DEPTH DRILLED (m)	ACCUMULATED POROSITY (m)	SAIL HEIGHT (m)	CONSOLIDATED LAYER THICKNESS (m)
								DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)				
FEB 21	1	1.0	0.5-1.0	M-H	0.22	-24	-	-	-	-	-	-	-	-	-	-	-	5.5	0.35	0.9	1.9
FEB 22	2	0.03	0.03	H	-	-22	-22	-	-	-	-	-	-	-	-	-	-	3.4	0	0.25	3.4
FEB 22	3	0.50	0.2-0.6	L-M	-	-25	-19	-	-	-	-	-	-	-	-	-	-	-	0.70	3.3	3.3
FEB 22	4	0.15	0.03	M	0.18	-25	-24	-	-	-	-	-	-	-	-	-	-	7.0	1.3	2.5	1.5
FEB 23	5	0.7	0.3-0.5	H	0.18	-25	-17	-	-	-	-	-	-	-	-	-	-	3.5	0	0.6	1.8
FEB 23	6	0.5	0.5-0.7	H	0.18	-25	-	-	-	-	-	-	-	-	-	-	-	3.0	0	0.6	1.7
FED 24	7	0	0	-	-	-33	-26	0.5	-18	1.0	-12	1.5	-8	2.0	-4	2.5	-1	2.5	0	0.5	1.4
FEB 24	8	0.7	0.6-0.7	H	0.18	-33	-12	0.5	-8	1.0	-7	1.5	-4	-	-	-	-	2.3	0	0	1.7
FEB 24	9	0.45	0.1-0.6	H	0.18	-33	-20	1.0	-14	1.5	-8	2.0	-10	2.5	-3	-	-	3.0	0.4	0.6	1.5
FEB 25	10	0.30	0.15-0.3	H	0.18	-34	-22	1.0	-15	2.0	-12	3.0	-8	3.5	-7	-	-	5.0	0.65	2.5	1.5
FEB 25	11	1.80	1.80	H	0.18	-34	-12	1.0	-8	1.8	-5	-	-	-	-	-	-	3.0	0.3	0.7	1.7
FEB 26	12	0.10	0.10-0.3	M-L	0.18	-33	-	1.0	-14	2.0	-16	2.8	-9	3.5	-2	-	-	3.5	0.3	2.0	1.5

* L - Light
M - Medium
H - Hard

SITE	SALINITY PROFILE					
	DEPTH (m)	SALINITY (°/oo)	DEPTH (m)	SALINITY (°/oo)	DEPTH (m)	SALINITY (°/oo)
13	0.1	3.1	1.0	2.6	2.5	4.5
14	0.1	4.0	0.4	3.2	1.1	2.9

Sea Water Salinity = 4 °/oo
Nominal Ice Thickness = 1.65 m

TABLE 7.1 INITIAL FIELD TRIP DATA - FEBRUARY

DATE DRILLED	SITE	SNOW COVER CHARACTERISTICS				TEMPERATURE PROFILE												RUBBLE PROFILE			
		LOCAL THICKNESS (m)	5m RADIUS THICKNESS (m)	SNOW TEXTURE	SNOW DENSITY (gm/cc)	AMBIENT AIR TEMP. (°C)	ICE SURFACE TEMP. (°C)	1		2		3		4		5		MAX. DEPTH DRILLED (m)	ACCUMULATED POROSITY (m)	SAIL HEIGHT (m)	CONSOLIDATED LAYER THICKNESS (m)
								DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)	DEPTH (m)	TEMP. (°C)				
MAR 22	1	0.85	0.7-1.5	M-H	0.22	-27	-18	1.3	-10	2.3	-6	-	-	-	-	-	-	5	0	0.9	4.1
MAR 22	2	0.02	0.02	M-H	0.18	-22	-22	1.0	-14	2.0	-6	-	-	-	-	-	-	3	0	0.3	3
MAR 21	3	0.15	0.17	M	0.18	-22	-18	1.0	-10	2.0	-7	-	-	-	-	-	-	3	0	1.2	1.8
MAR 21	4	0	0-0.1	M	0.18	-23	-23	1.0	-21	2.0	-18	3.0	-14	4.0	-9	5.0	-5	7	0.4	2.5	3.0
MAR 21	5	0.13	0.1-0.2	M-H	0.18	-23	-19	1.0	-11	2.0	-7	-	-	-	-	-	-	5	0.3	1.05	2.4
MAR 22	6	0.85	0.8-1.0	M	0.18	-22	-12	1.5	-7	-	-	-	-	-	-	-	-	4	0.3	0.7	2.8
MAR 22	7	0	0	-	0.18	-20	-20	1.0	-16	2.0	-8	-	-	-	-	-	-	4	0	0.4	2.6
MAR 23	8	0.8	0.4-1.0	M	0.18	-24	-9	1.0	-7	2.0	-2	-	-	-	-	-	-	3	0	-0.1	2.5
MAR 23	9	0.45	0.2-0.6	M-H	0.18	-24	-17	1.0	-14	1.8	-8	2.8	-4	-	-	-	-	5	0.28	1.0	2.5
MAR 23	10	0.8	0-1.5	M	0.18	-18	-12	2.0	-12	2.7	-10	4.2	-5	5.0	-1	-	-	5	0	2.0	3.0
MAR 23	11	1.5	1.2-1.8	M	0.18	-18	-12	1.0	-8	2.0	-5	2.0	-1	-	-	-	-	4	0	1.0	2.0
MAR 24	12	0.06	0.06-0.1	M	0.18	-25	-23	1.0	-19	2.0	-14	3.0	-8	4.0	-1	-	-	6	0.36	2.1	1.6

Nominal Ice Thickness = 2.0 m

TABLE 7.2 SECOND FIELD TRIP - MARCH

8.0 Comparison of Measurements with Analytical Models

In this chapter the measurements obtained at Minuk Island and at the Esso facility in Calgary are compared with predictions made using the analytical models of reference 1.

In Section 8.1 growth calculations and measurements are compared. In Section 8.2 time-dependent settlement calculations and measurements are compared.

8.1 Analytical Model for Thermal Consolidation of Ice Rubble

Under a separate contract to Canada Marine Engineering Ltd., from Public Works Canada, analytical models for the refreezing and mechanical properties of broken ice have been developed. The reader is referred to the contract report (reference 1) for the details of these analytical models: only a summary description is presented in this report.

A computer program ICEGROW calculates the refreezing of broken ice and predicts the mechanical properties of the refrozen thickness. The program treats the ice rubble as a multi-layered one-dimensional material consisting of a snow cover, a sail (unsaturated rubble), a refrozen layer, and a partially refrozen keel (saturated). The program assumes steady-state conduction through the various layers, although certain transients which occur when the rubble first forms are accounted for in the methodology. Heat flow from the ice/snow surface is by long wave radiation and convection, therefore both air temperature and wind speed are accounted for in the program. (Evaporative heat transfer is ignored because of the barrier which an ice cover provides and because of the generally low vapour pressure of cold air. Also, solar radiation is ignored because of its generally small effect during the growth period at high latitudes.)

In addition to predicting ice growth, the program also calculated mechanical properties of the refrozen layer using the algorithms which can be adjusted by the user.

8.1.1 Typical Input and Output Data for ICEGROW

There are two input files. The first is called "ICEGROW.DAT" and contains the run time, input parameters, and options. Input file parameters are described in Table 8.1. (Note that lines 54 to 62 relate to mechanical properties coefficients.) The second file "DAYVAL.DAT" contains the daily values for air temperature, wind speed, long wave radiation and snow cover.

Typical output data is given in Table 8.2.

8.1.2 Comparison of Measurements in Ice Basin with Analytical Model

As already described, the refreezing of ice rubble in the ice basin was monitored over a 30 day period during February, 1986. In parallel, the growth of sheet ice in the same ice basin was also monitored. Because no measurements of long wave radiation were possible, it was decided to calibrate the model for long wave radiation first, using the sheet ice growth measurements. The ICEGROW program was therefore run with an initial porosity of 1.0 (as required for sheet ice growth), and with three values of long wave radiation, 35, 40 and 45 W/m^2. The appropriate daily values of air temperature and wind speed measured at the ice basin were used in the program.

The results of these calculations are plotted in Figure 26. (Print out of the input and output data are given in Appendix A.)

Inspection of Figure 26 indicates that the results from ICEGROW are not very sensitive to the long wave radiation. It was therefore decided to use a value of 40 W/m^2 in the remaining simulations.

The results also show reasonably good agreement between measured and calculated ice growth, at least up until day 21. After day 23, the weather became much warmer. The reduction in ice thickness predicted by ICEGROW did not accurately track the measured thickness reduction (which was much more pronounced). The divergence, after about day 21 between measured and

predicted, is likely due to incorrect modeling of radiation. During the latter 10 days of the experiment, sunny days became more prevalent and air temperatures were higher. Under these conditions both incoming solar and long wave radiation are increased significantly. As the program was primarily compiled to predict ice growth (not decay) no attempt has been made in this study to match the decrease in ice thickness by modifying the radiation component in the computations.

The ICEGROW program was next run to simulate the refreezing of the ice rubble. These simulations were performed with the appropriate daily values of air temperature and wind, and with a constant daily long wave radiation component of 40 W/m^2. However, sensitivities were performed with respect to initial porosity and sail height. Computer inputs and outputs for these cases are given in Appendix B, and the results plotted in Figure 27. A reasonable fit to the measured data during the growth period was obtained with an initial porosity of 0.3 and sail height of 0.25 m. The average of all the initial 20 porosity measurements was in fact 0.3; and a sail height of about 0.25 m was typical during the growth period. Therefore it appears that the ICEGROW model for rubble refreezing is in quite good agreement with the measured values.

8.1.3 Comparison of Measurements in the Arctic with Analytical Model

This is a more difficult excercise because of the variability in field conditions between sites and also because of the apparent inconsistancies in some of the field data. For example, site 1 (see Figure 22) shows the largest consolidated thickness (of all sites) at greater than 4 m. Yet almost one metre of snow was measured there, compared to zero snow thickness at site 7, where the consolidated thickness only reached 2.6 m. Without even running the ICEGROW program we know that, all other things being equal, it would predict less consolidated thickness at site 1 than site 7, which is the reverse of the measurements. Other apparent anomalies exist in the measured data. These can be due to several factors, including:

- Variations in initial porosities between sites.
- Changes in snow thicknesses during the ice growth period.
- Changes in porosities with depth and time due to creep settlement.
- Measurement errors in estimating consolidated thickness.
- Variation in local wind speeds across the rubble caused by variation in surface geometry.
- Differential settlement in the ice rubble (when settlement occurs ice growth will be at both the top and bottom of the consolidated layer).
- Variations in rubble formation dates between sites.

Having defined possible reasons for the measurement anomalies we can now look at the results of using ICEGROW at three typical locations, sites 4, 9 and 10. Parametric runs were performed to examine the effects of changing the snow thickness (T_s), the initial porosity (P) and the initial

ice temperature (A) when the rubble was formed (for sites 9 and 10 only).

Figure 28 shows the measured and calculated results for site 4. Porosity and snow thickness were varied with the initial ice temperature kept constant at -14 °C. Daily air temperatures and winds recorded at Minuk were used in the program. The results indicate significant sensitivity of the refrozen layer thickness with changes in P and T_s, but no single combination of those chosen matches that measured data. Zero snow thickness and a porosity of 0.32 gives a good match to the March measurement, but under predicts the April measurement. Whereas zero thickness and an initial porosity of 0.28 gives a good match to the April measurement, but over predicts the refrozen layer in March.

At site 9, a reasonable fit to the measured data is obtained with a snow thickness of 0.45 m (the measured value), and a porosity of 0.25 (see Figure 29). Generally it is considered that the initial porosity of the ice rubble at Minuk was close to 0.25. This estimate is based partly on the measurements of voids in the sails at Minuk, but mostly on the measurements of porosity obtained in the Esso ice basin (which were easier to perform).

Figure 30 shows the results for site 10, where all three influencing parameters in the ICEGROW program were varied (i.e. snow thickness, porosity and initial ice temperature). The results show that the best fit is obtained with an initial porosity of 0.25, a snow cover of 0.3 m and an initial ice temperature of -14 °C.

In general, the predictions for the refrozen layer thickness in the rubble in the arctic do not match very well the measured thicknesses. Possible reasons for this disagreement are discussed in the Conclusions and Recommendations.

8.2 Analytical Model for Time-Dependent Bearing Settlement

The reader is referred to reference 1 for a detailed description of the analytical model to predict the time-dependent bearing capacity of grounded ice rubble. The model assumes a two layered system, modeling the rubble as an unsaturated sail and a saturated grounded keel (Figure 31). A loaded area of square geometry is assumed to act at the upper surface. A simplified decay of compressive stress is assumed based on a "spreading angle" θ. The compressive stress is calculated with depth through the ice rubble. At each level in the ice rubble the strain and deflection associated with the compressive stress are calculated, these are then integrated over the full rubble thickness to obtain total deformation.

Three contributions to deformation are calculated.

(1) an elastic and primary creep deformation based on a pseudo elastic modulus,

(2) an unrecoverable deformation due to ice crushing in the areas of contact between ice blocks, and

(3) a time-dependent secondary creep deformation. This uses Glen's law suitably modified for the stress concentrations between ice blocks.

The theory described above is assembled into a simple computer program "CREEP".

8.2.1 Input Data for CREEP

The input data required for CREEP is as follows:

P	- applied load	(kN)
A	- size of loaded area (A X A)	(m)
THETA	- angle of spreading of compressive stress	(degrees)
H1	- sail thickness	(m)
H2	- keel thickness	(m)
RHO 1	- ice density	(kNm^{-2})
RHOW	- water density	(kNm^{-2})
GAM1	- porosity of sail	
GAM2	- porosity of keel	
ES	- pseudo elastic modulus for sail	(kPa)
EK	- pseudo elastic modulus for keel	(kPa)
SIGSC	- crushing strength of ice in sail	(kPa)
SIGKC	- crushing strength of ice in keel	(kPa)
BS	- creep coefficient in sail	($MPa^{-3}s^{-1}$)
BK	- creep coefficient in keel	($MPa^{-3}s^{-1}$)
K	- stress concentration factor (between 1 and 10) in creep equation	
F	- ice crushing factor (about 3) which depends on the shape of ice blocks	
M	- number of slices into which sail and keel are divided when performing the calculations	
T	- number of days over which calculation is run	(days)

Some further discussion of some of the input parameters is warranted. B is the creep 'constant' in Glen's law, i.e.

$$\text{Strain Rate} = B\sigma^3$$

(where σ is stress)

B is dependent on ice temperature, salinity and crystal structure. It is often expressed as:

$$B = A \exp(-Q/RT)$$

where: R is the gas constant (8.314 J/mol °K),
T is the ice temperature in °K,
Q is the activation energy (65 KJ/mol), and
A depends on ice type.

For columnar ice, Sanderson (reference 3) reports that several sources of experimental data fit the creep equation if

$$A = 5.5 \times 10^4 \text{ MPa}^{-3}\text{s}^{-1} \text{ for warm ice.}$$

In the theory developed in reference 1 it is suggested that Glen's law for secondary creep be modified to the form:

$$\text{Strain Rate} = B\left(\frac{K\sigma}{1-\gamma}\right)^3$$

where K is a stress concentration factor to account for the contact stresses between ice blocks, and γ is the rubble porosity. K is best obtained by calibration with experimental data however a simple model for ice rubble is analyzed in reference 1 to derive a typical value for K. This was found to be about 4.0 for an ice rubble model made up of square ice blocks. The same model gave a value for F of about 3.0.

Exercising the theoretical model indicates that typically the elastic and crushing components are small compared with the creep component of deflection. Also, that the results are very sensitive to K, and the porosity γ.

8.2.2 Comparison of Measurements in Ice Basin with Analytical Model

The configuration for the bearing settlement test in the ice basin has already been described (Figure 12). The input data for CREEP corresponding to the test arrangement is shown below (for K = 4.0), the output data is also shown below, and gives the various deformation components and their totals as a function of time. It should be noted that the survey posts are really indicating the keel deformation (because they are frozen in at the water line). Whereas the settlements obtained by surveys on the loading box will indicate total deformation of both keel and sail.

Figure 32 shows a comparison of measured settlement with theory for the keel only, and Figure 33 a comparison for the total rubble thickness.

It will be noted that with a K value of about 5 a reasonably good match is obtained up to about 5 days (120 hours). Beyond that time the measured settlement rate starts to increase, suggesting the onset of tertiary creep (for which the theory does not apply). In most practical applications the onset of tertiary creep is to be avoided. Further experimental and theoretical modeling is required to predict the time or strain at which tertiary creep failure begins.

Input Parameters

P =	167.0	A =	2.4
THETA =	75.0		
H1 =	1.0	H2 =	2.7
RHOI =	8.900	RHOW =	10.300
GAM1 =	.300	GAM2 =	.300
ES =	350000.0	EK =	100000.0
SIGSC =	2000.0	SIGKC =	1000.0
BS =	.3000E-04	BK =	.9000E-04
K =	4.000	F =	3.000
M =	10	T =	10

Edit input parameters? n
Save data on diskette? y
Input parameters saved on file: crdat

Time Dependent Deflection of Ice Rubble

	SAIL (in meters)			KEEL (in meters)			
Day	Elastic	Crush	Creep	Elastic	Crush	Creep	Total
1	.0000761	.0044419	.0091864	.0004652	.0155072	.0226872	.052364
2	.0000761	.0044419	.0183727	.0004652	.0155072	.0453743	.084237
3	.0000761	.0044419	.0275591	.0004652	.0155072	.0680615	.116111
4	.0000761	.0044419	.0367454	.0004652	.0155072	.0907487	.147985
5	.0000761	.0044419	.0459318	.0004652	.0155072	.1134358	.179858
6	.0000761	.0044419	.0551182	.0004652	.0155072	.1361230	.211732
7	.0000761	.0044419	.0643045	.0004652	.0155072	.1588101	.243605
8	.0000761	.0044419	.0734909	.0004652	.0155072	.1814973	.275479
9	.0000761	.0044419	.0826772	.0004652	.0155072	.2041845	.307352
10	.0000761	.0044419	.0918636	.0004652	.0155072	.2268716	.339226

TABLE 8.1
ICEGROW.DAT INPUT FILE PARAMETERS

Line	Variable Name	Description
1.	TITLE	32-character run title
2.	ISMON	starting date month number; 1=January 2=Feb, etc.
3.	ISDAY	starting date day, of month ISMON
4.	IEMON	ending date month number
5.	IEDAY	ending date day, of month IEMON
6.	ISHP1	time in hours, before the first ship arrives ... can be 0.
7.	ISHP2	interval in hours, between ships 1 and 2, 2 and 3 etc. If ISHP2 is 0 and ISHP1 is >0 then ISHP2 is set to ISHP1. If ISPH1 and ISHP2 are both 0 then there are no ships
8.	IATMP	= 0, use constant air temp; = 1, use daily value from table
9.	IWNDY	= 0, use constant wind speed; = 1, use daily value from table
10.	ILWR	= 0 use constant long wave radiation; = 1, use daily value from table
11.	ISNCVR	= 0, use constant snow cover; = 1, use daily value from table
12.	ISALIN	= 0, use Cox and Weeks calculation; = 1, use gradient
13.	IODAY	= n; output values to table every n days
14.	ISURF	= 0, allow negative sensible heat and ice growth; = 1 to not allow
15.	ISENS	= 0, allow surface temperature to be less than air temperature; = 1 do not allow
16.- 28.	IPLOT(n)	= 1, plot nth output table entry vs time = 0, do not plot. Eg. if IPLOT7=1 plot elastic modulus vs. time
29.	ATINP	constant air temperature, °C; ignored if IATMP above = 1
30.	VWINP	constant wind speed, m/sec; ignored if IWNDY above = 1
31.	QLINP	constant long wave radiation, w/m^2; ignored if ILWR above = 1
32.	HSNINP	constant snow cover, m; ignored if ISNCVR above = 1
33.	TCO	average sail rubble temperature at start of run, °C
34.	HSAIL	sail height, m
35.	GAMI	porosity of sail rubble; must > 0
36.	CSNOW	sensible heat transfer coefficient of snow
37.	HICE	ice thickness at strait of run, m, if set = 0, program defaults to 0.001 m
38.	SALTOP	salinity at top of ice, ppt; used only if ISALIN = 1
39.	SALBOT	salinity at bottom of ice, ppt; used only if ISALIN = 1
40.	XKSINP	thermal conductivity of snow, w/m°C
41.	TF	freezing temperature of water, °C
42.	TW	average temperature of water, °C
43.	CISNOW	specific heat of snow, KJ/kg°C
44.	SISAIL	initial average salinity of sail rubble at start of run, ppt; also equals salinity of keel rubble
45.	CSAIL	sensible heat transfer coefficient of sail rubble
46.	CSICE	sensible heat transfer coefficient of ice
47.	GAMSUB	porosity of keel rubble for use with ships track routine; no prior ice growth by program
48.	GAMSTI	average porosity of rubble immediately after ship pass
49.	HKEEL	keel depth for use with ships track routine
50.	ALPHA	coefficient for degree day method
51.	SAVINP	average ice salinity for use with ships track routine, ppt; if no prior ice growth by program
52.	TAVINP	average ice temperature for use with ships track routine, ppt; if no prior ice growth by program
53.	FACLOS	loss factor, i.e. fraction of ice displaced, after each ships pass
54.	COEFFA	coefficients in elastic modulus function
55.	COEFFB	
56.	COEFFC	coefficients in tensile or flexural strength function
57.	COEFFD	
58.	COEFFE	coefficients in crushing strength function
59.	COEFFF	
60.	COEFFN	brine volume 'power' in elastic modulus function
61.	COEFFN	brine volume 'power' in tensile or flexural strength function
62.	COEFFD	brine volume 'power' in crushing strength function

TABLE 8.2 TYPICAL RESULTS FROM ICEGROW

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

SAMPLE ICEGROW INPUT

INPUT PARAMETERS AND OPTIONS:

Snow cover	.10 m
Initial ice thickness	.700 m
Initial soil thickness	.00 m
Initial keel thickness	10.00 m
Temperature of water	-1.00 oC
Freezing temperature of water	-1.80 oC
Average initial rubble temperature	-1.00 oC
Initial rubble porosity	1.00
Porosity of rubble after ship's track	.35
Interblock frozen rubble porosity	.34
Initial salinity of soil	10.00 ppt
Heat transfer coefficient of ice	.00175
Heat transfer coefficient of soil	.00175
Heat transfer coefficient of snow	.00175
Specific heat of snow	.42000KJ/KgoC
Thermal conductivity of snow	.21000 W/moC
Degree day method coefficient	.00
Coefficient "A"	5230.00
Coefficient "B"	-13000.00
Coefficient "C"	.81
Coefficient "D"	-2.03
Coefficient "E"	1.70
Coefficient "F"	-3.00
Coefficient "H"	.50
Coefficient "N"	.50
Coefficient "O"	.50
Starting day	NOV 25
Ending day	APR 30
Total number of days	157
Air temperature method	DAILY
Wind velocity method	DAILY
Long wave radiation method	DAILY
Snow cover method	CONSTANT
Salinity method	AVERAGE

Ice porosity due to interblock freezing = 1.000

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (Ly/day)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	PERMEAT CAPACITY UP (cm)	PERMEAT CAPACITY DOWN (cm)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 NOV 25	-13.00	5.00	[illegible]	.100	.707	.891	1648.	.2534	.859	.922	.8642	6.76	-4.91
2 NOV 26	-14.60	3.90	[illegible]	.100	.711	.878	1678.	.2569	.851	.924	.8804	6.73	-5.10
3 NOV 27	-11.00	8.20	[illegible]	.100	.720	.899	1595.	.2715	.872	.920	.8180	6.74	-4.39
4 NOV 28	-14.60	4.10	[illegible]	.100	.724	.889	1667.	.2743	.873	.921	.8171	6.73	-4.23
5 NOV 29	-6.10	5.00	00.00	.100	.731	.884	1692.	.1990	.855	.916	.7910	6.72	-3.43
6 NOV 30	-6.30	4.20	00.00	.100	.733	.881	1160.	.1995	.860	.917	.7589	6.71	-3.38
7 DEC 1	-10.90	4.20	00.00	.100	.733	.886	1679.	.2266	.870	.922	.8345	6.72	-4.45
8 DEC 2	-15.90	2.50	00.00	.100	.733	.873	1701.	.2811	.845	.927	.9040	6.72	-5.39
9 DEC 3	-17.00	3.90	00.00	.100	.738	.871	1847.	.2909	.842	.928	.9193	6.71	-5.90
10 DEC 4	-15.60	4.50	00.00	.100	.744	.875	1799.	.2764	.848	.927	.8968	6.69	-5.41
11 DEC 5	-13.50	11.90	00.00	.100	.733	.887	1568.	.2481	.864	.925	.8532	6.68	-4.67
12 DEC 6	-19.70	14.20	00.00	.100	.754	.870	1879.	.2956	.841	.930	.9260	6.68	-6.00
13 DEC 7	-25.20	3.10	00.00	.100	.725	.860	2123.	.3310	.833	.934	.9831	6.68	-7.68
14 DEC 8	-29.40	1.40	00.00	.100	.760	.856	2259.	.3511	.830	.937	1.0184	6.67	-8.46
15 DEC 9	-32.00	2.00	00.00	.100	.769	.851	2386.	.3578	.830	.939	1.0232	6.66	-8.82
16 DEC 10	-29.60	3.10	00.00	.100	.782	.855	2251.	.3312	.831	.939	1.0148	6.64	-8.01
17 DEC 11	-26.00	10.00	00.00	.100	.795	.859	2133.	.3336	.833	.938	.9899	6.62	-7.50
18 DEC 12	-26.20	8.60	00.00	.100	.804	.859	2145.	.3371	.835	.939	.9926	6.60	-7.63
19 DEC 13	-26.20	6.10	00.00	.100	.817	.858	2180.	.3393	.835	.940	.9961	6.59	-7.72
20 DEC 14	-28.50	11.20	00.00	.100	.829	.869	1997.	.2990	.845	.932	.9309	6.56	-8.14
21 DEC 15	-27.20	14.40	00.00	.100	.836	.871	1837.	.2908	.848	.936	.9169	6.55	-8.03
22 DEC 16	-23.30	9.20	00.00	.100	.833	.861	2101.	.3277	.837	.941	.9778	6.55	-7.19
23 DEC 17	-27.00	3.60	00.00	.100	.837	.855	2263.	.3513	.833	.943	1.0133	6.55	-8.27
24 DEC 18	-21.80	6.10	00.00	.100	.844	.853	2234.	.3389	.834	.947	1.0075	6.54	-8.68
25 DEC 19	-25.30	6.10	00.00	.100	.850	.857	2291.	.3472	.838	.946	1.0249	6.52	-7.75

9.0 Conclusions and Recommendations

The major focus of this research project was to gather field data and large-scale experimental data on the properties of ice rubble, the main objective being to examine the refreezing of ice rubble and to obtain measurements which could be used to test theoretical models. The original planned approach was to conduct all the measurements in the Arctic on a grounded rubble field surrounding an artificial island. It was to rely heavily on logistical support from an oil company. Unfortunately due to operational problems the company could not allow a field presence during the early part of the winter in the Arctic. The reduction in scope of the Arctic program resulted in the Arctic measurements being less useful. On the other hand the company made available to the project their large ice test basin in Calgary. The work conducted in the ice basin, both on thermal consolidation and on bearing settlement, was successful and has yielded good data against which to test the analytical models.

From the thermal consolidation tests in the ice basin, the following points can be made:

- The measurements indicated (as expected) that the refreezing of ice rubble proceeds at a faster rate than the growth of sheet ice.

- The analytical model gives good agreement with the measured data during the ice growth period (when air temperatures were below freezing).

- When the weather warmed up the ablation of the ice proceeded faster than predicted by the analytical model. This is thought due to the effects of the incoming solar radiation not being correctly modeled in the analytical model. Further development of the analytical model is warranted on this topic.

From the measurements in the Arctic the following points can be made:

. By late March the maximum measured refrozen thickness in the ice rubble was greater than 4 m. This is greater than twice the normal ice growth of sheet ice for the same period.

. In general, the presence of snow cover and a rubble sail inhibited the rate of refreezing of the ice rubble. But there were anomalies in this general trend. For example, some locations with low sails and minimal snow cover did not have the greatest refrozen thickness, and vice-versa.

. There are a number of possible explanations for these anomalies, e.g.

- initial porosities at the various sites may have been different.

- settlement of the rubble may have caused varying porosity with time and depth.

- settlement of the ice rubble may have caused refreezing at both top and bottom of the refrozen layer.

- snow cover may have varied with time as a function of drifting caused by variable winds.

- local winds may have been affected by the presence of the island and variation in surface roughness of the ice rubble.

- different areas of the ice rubble may have formed at different times.

- It is also noted that measurements of ice rubble porosity is only approximate. A better technique than estimation of void thickness by augering is required. At the same time it is noted that the results from the analytical model are very sensitive to the porosity used.

- Because of the above mentioned anomalies, it is not surprising that the analytical model did not match the Arctic measured data as well as it did the ice basin measurements.

The time-dependent bearing settlement test conducted in the ice basin has yielded useful large-scale data, albeit for warm ice rubble. From the results of the experiment it is noted that:

- For an applied stress at the surface of about 30 kPa, a settlement of about 0.5 m occurred in the 3.7 m thick ice rubble over a period of about 6 days.

- Tertiary creep deformation occurred after about 5 days (0.35 m deflection). Failure of the ice rubble occurred after about 9 days.

- Up until the onset of tertiary creep, the analytical model (with a stress concentration factor of between 4 and 5) matched the measured data quite well.

- A criteria for the time (and/or gross strain) for the onset of tertiary creep needs to be developed.

- The analytical model needs to be tested against measurements conducted on colder ice rubble.

10.0 Acknowledgments

Without the support given by Esso Resources Canada Ltd, this project could not have been conducted. The support and enthusiasm shown by Esso staff is acknowledged. Esso staff involved in the project include Jim McDougall, Dave Janes, Rob Patterson, and Gilles Truchon.

Doug Roth and Vern Penner, of Canada Marine Engineering Ltd. are thanked for their enthusiastic and skillful contributions to the project.

The study was supported by Public Works Canada. Moe Cheung, the scientific authority, is thanked for his ideas and support. Staff from the National Research Council of Canada also provided useful advice and field support; Bob Frederking and Mo Sayed are thanked for their contribution.

11.0 References

(1) Canada Marine Engineering Ltd., K.R. Croasdale and Associates Ltd., Swan Wooster Engineering Co. Ltd., University of Alberta (Dept. of Civil Engineering), "Analytical Models for Broken Ice Zones." C.M.E.L. Report No. 1038, Prepared for Public Works Canada, March, 1986.

(2) Graham, B.W., R.E. Potter, K.N. Wood and G. Comfort, "Rubble-Protected Drilling System Developments." Proceedings of the Seventh International Symposium on Ice, International Association of Hydraulic Research, Hamburg, F.R. Germany, Volume III, pp. 113 - 125, August 27 - 31, 1984

(3) Sanderson, T.J.O., "Theoretical and Measured Ice Forces on Wide Structures." Proceedings of the Seventh International Symposium on Ice, International Association of Hydraulic Research, Hamburg, F.R. Germany, Volume IV, pp. 151 - 207, August 27 - 31, 1984.

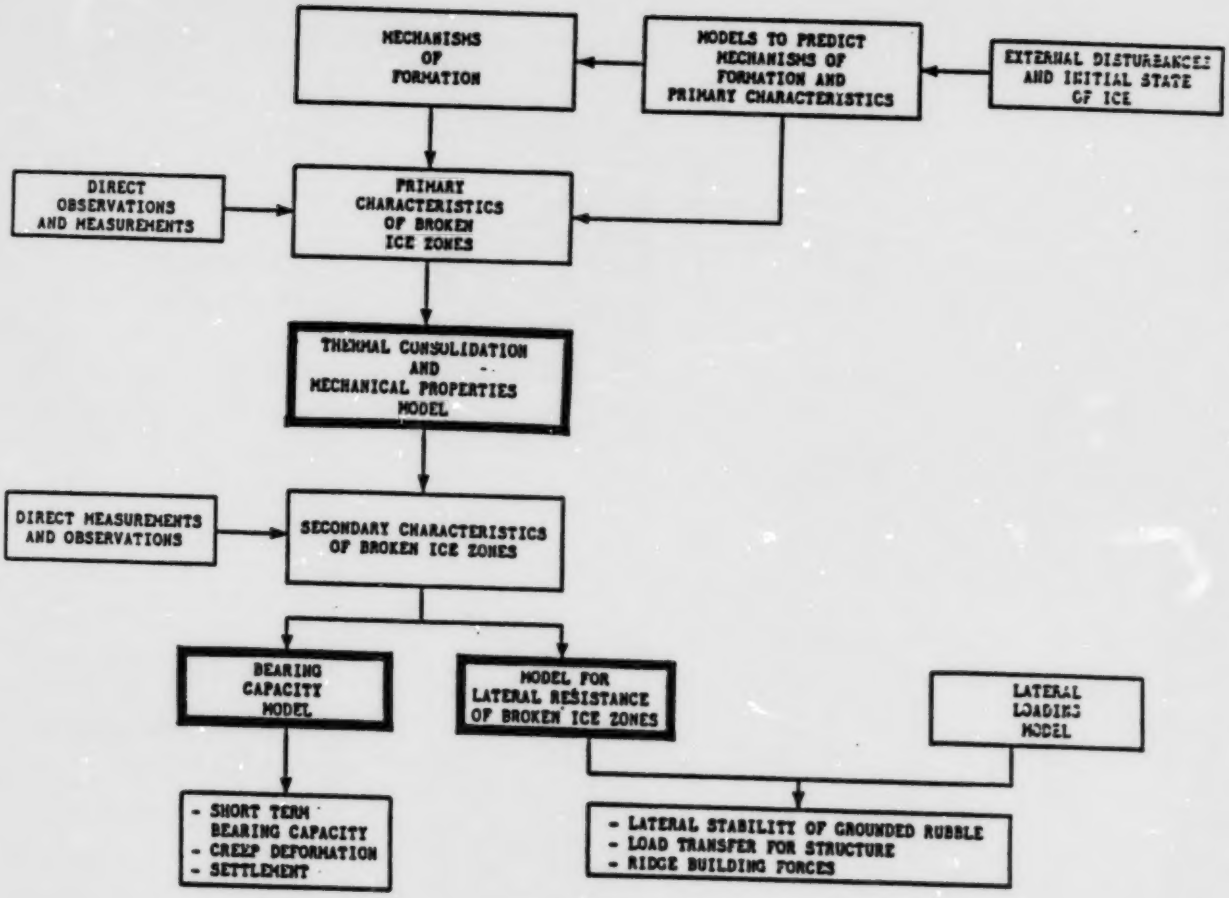

MECHANISMS OF FORMATION
MODELS TO PREDICT MECHANISMS OF FORMATION AND PRIMARY CHARACTERISTICS
EXTERNAL DISTURBANCES AND INITIAL STATE OF ICE
DIRECT OBSERVATIONS AND MEASUREMENTS
PRIMARY CHARACTERISTICS OF BROKEN ICE ZONES
THERMAL CONSOLIDATION AND MECHANICAL PROPERTIES MODEL
DIRECT MEASUREMENTS AND OBSERVATIONS
SECONDARY CHARACTERISTICS OF BROKEN ICE ZONES
BEARING CAPACITY MODEL
MODEL FOR LATERAL RESISTANCE OF BROKEN ICE ZONES
LATERAL LOADING MODEL
- SHORT TERM BEARING CAPACITY
- CREEP DEFORMATION
- SETTLEMENT
- LATERAL STABILITY OF GROUNDED RUBBLE
- LOAD TRANSFER FOR STRUCTURE
- RIDGE BUILDING FORCES

FIGURE 1 OVERALL LOGIC AND ANALYTICAL MODELS FOR BROKEN ICE ZONES.

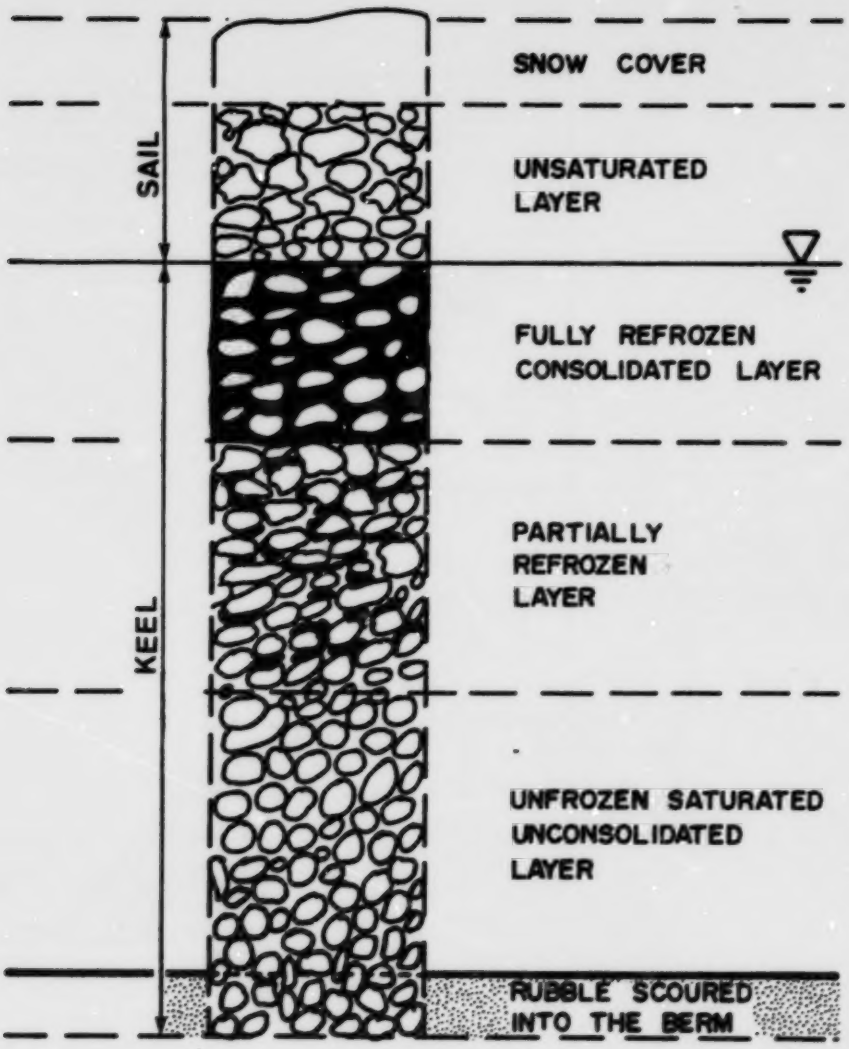


FIGURE 2 IDEALIZED MODEL OF THE LAYERS WITHIN A GROUNDED RUBBLE PILE

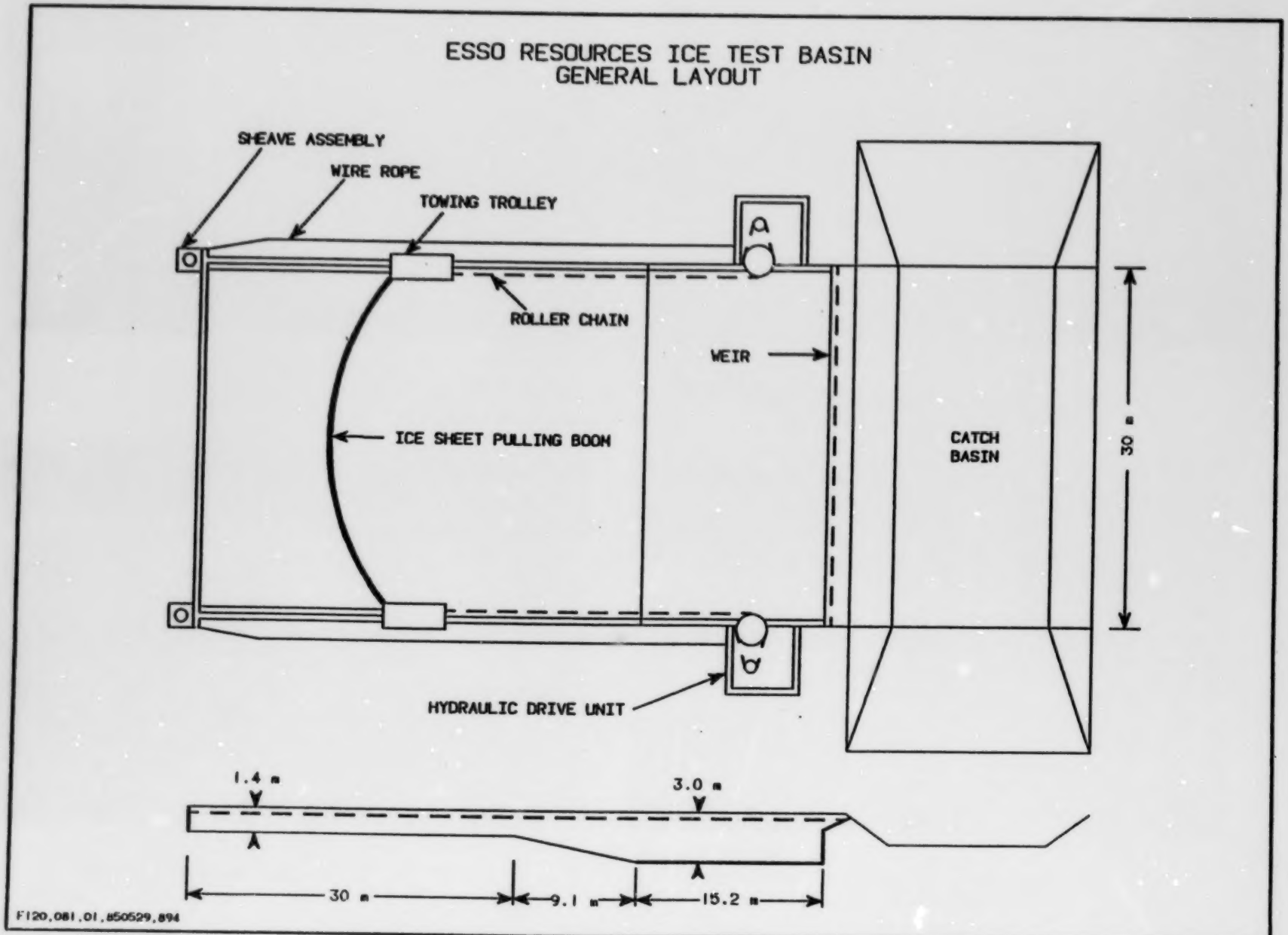

ESSO RESOURCES ICE TEST BASIN
GENERAL LAYOUT
SHEAVE ASSEMBLY
WIRE ROPE
TOWING TROLLEY
ROLLER CHAIN
WEIR
ICE SHEET PULLING BOOM
CATCH BASIN
30 m
HYDRAULIC DRIVE UNIT
A
B
1.4 m
3.0 m
30 m
9.1 m
15.2 m
F120,081,01,850529,894

Figure 3

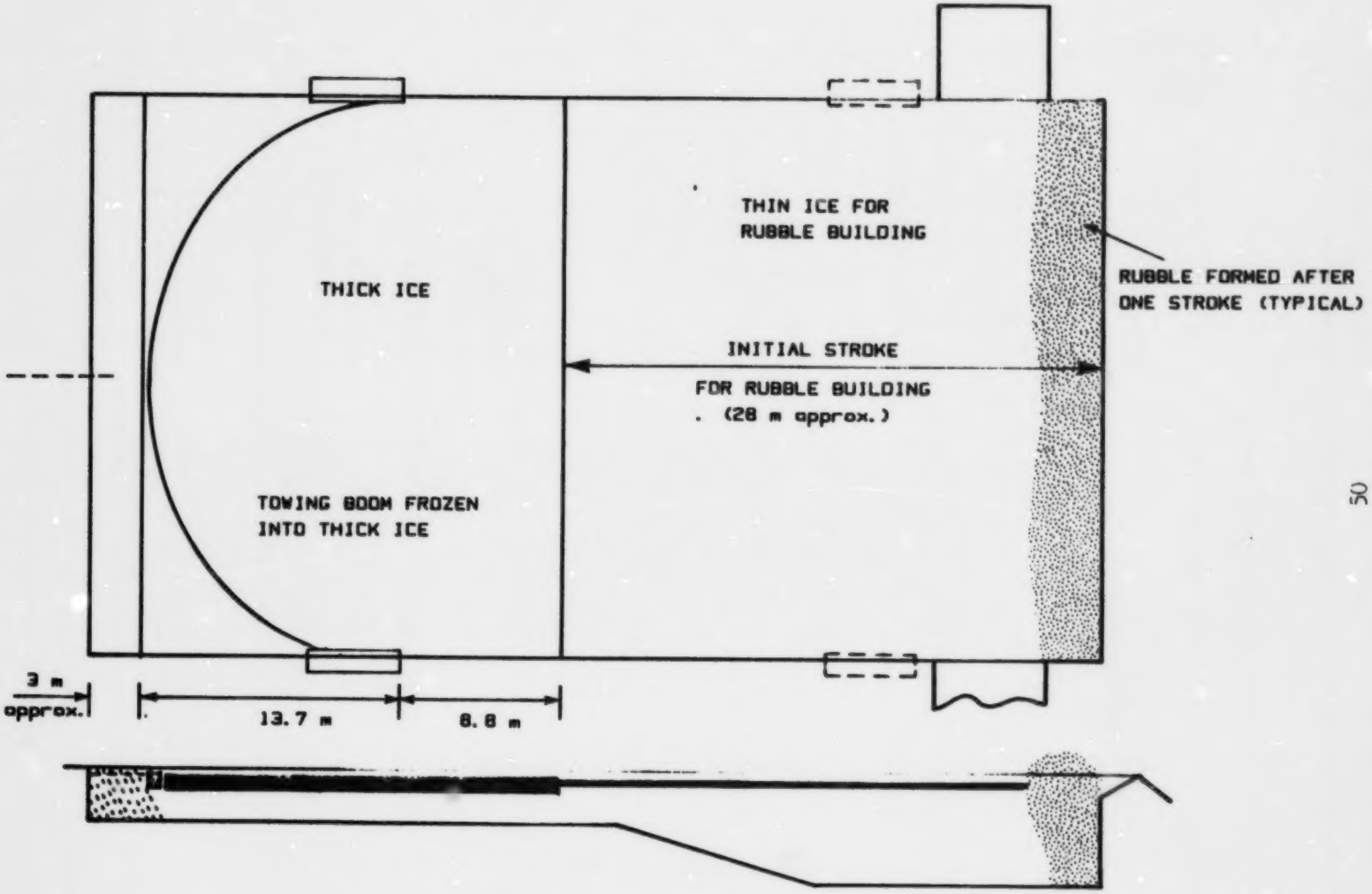


FIGURE 4 ORIGINAL SCHEME FOR GENERATING ICE RUBBLE IN THE ICE BASIN

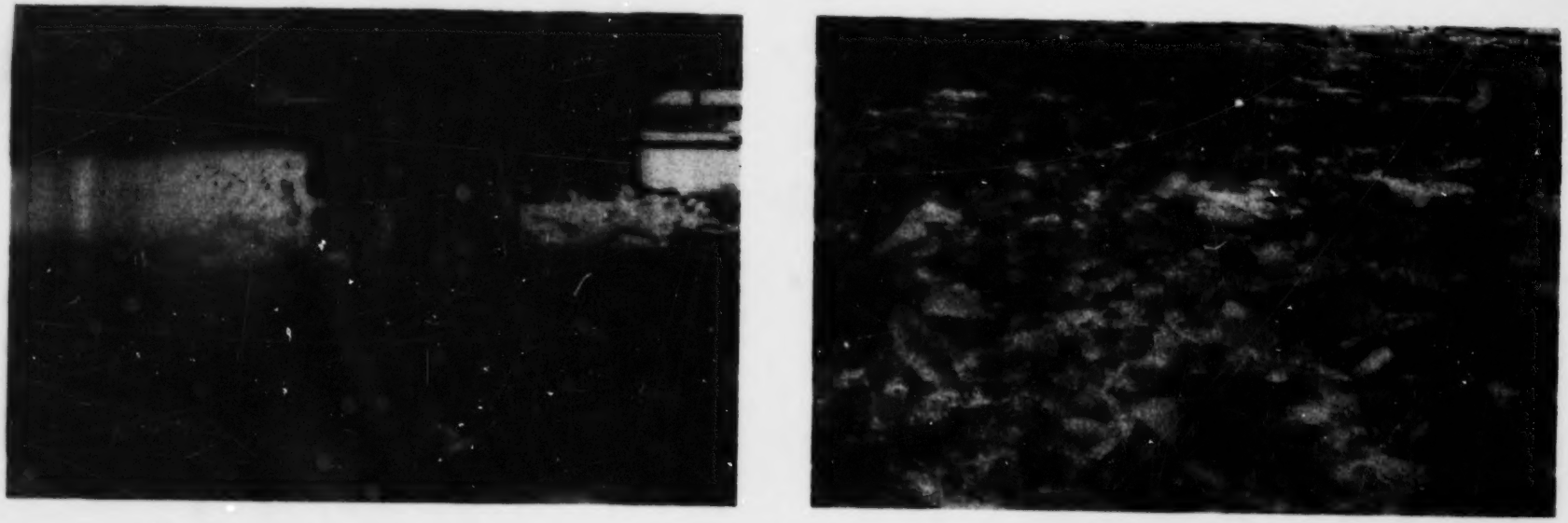
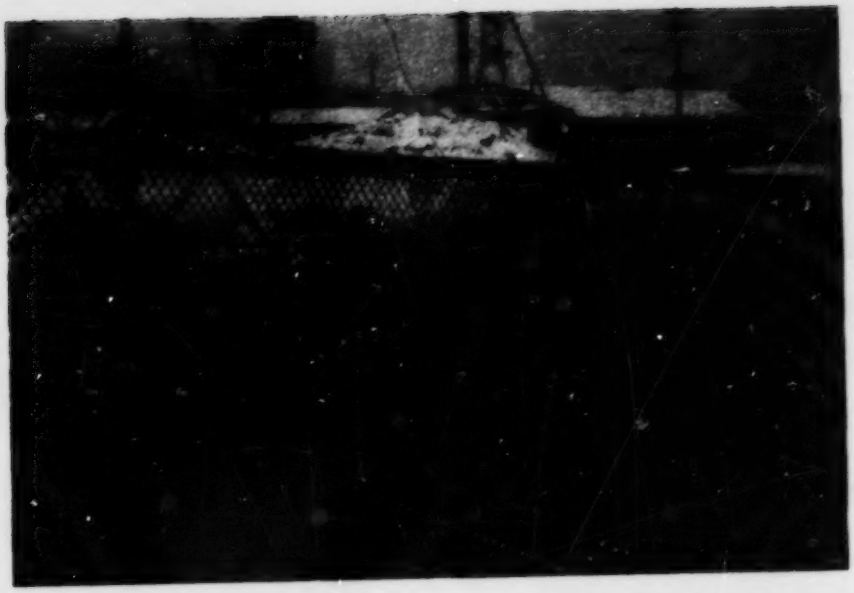


Figure 5 RUBBLE BUILDING IN THE ICE BASIN

Figure 6 RUBBLE FIELD IN ICE BASIN

Figure 7 THE GROUNDED ICE RUBBLE FOR ICE REFREEZING MEASUREMENTS



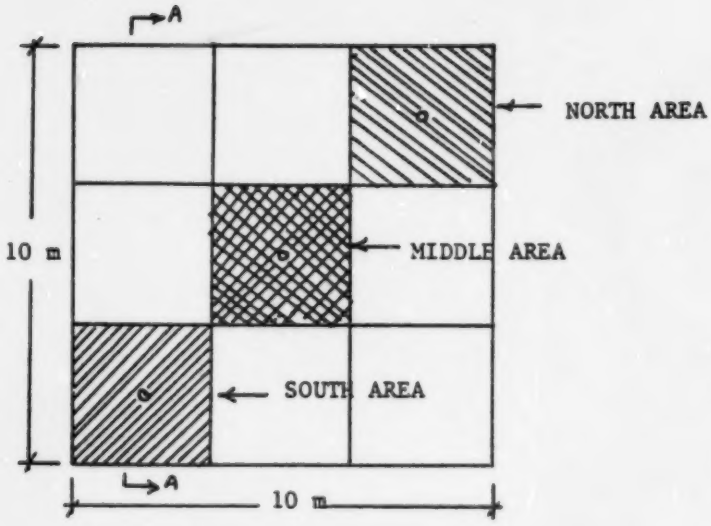
ICE RUBBLE RETAINING CAGE BEING PLACED
IN THE ICE BASIN

BEARING SETTLEMENT TEST

LOADING BOX BEING PLACED

Figure 8

CONFIGURATION OF RATE OF THERMAL CONSOLIDATION EXPERIMENT



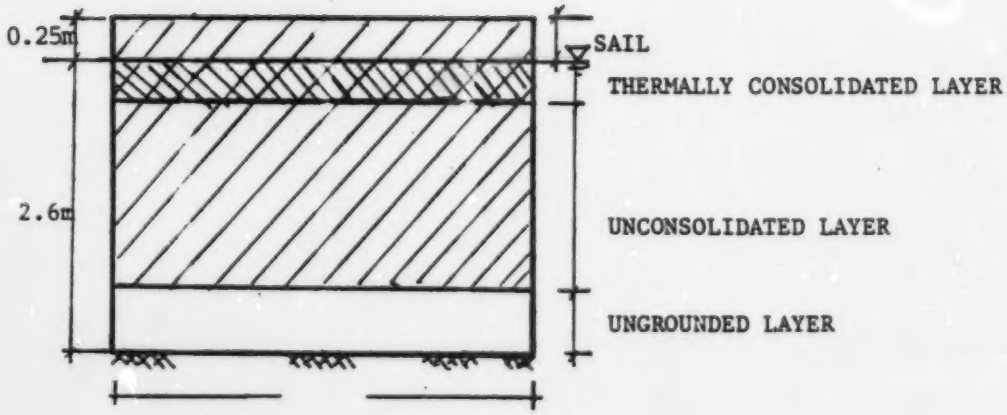


Figure 9

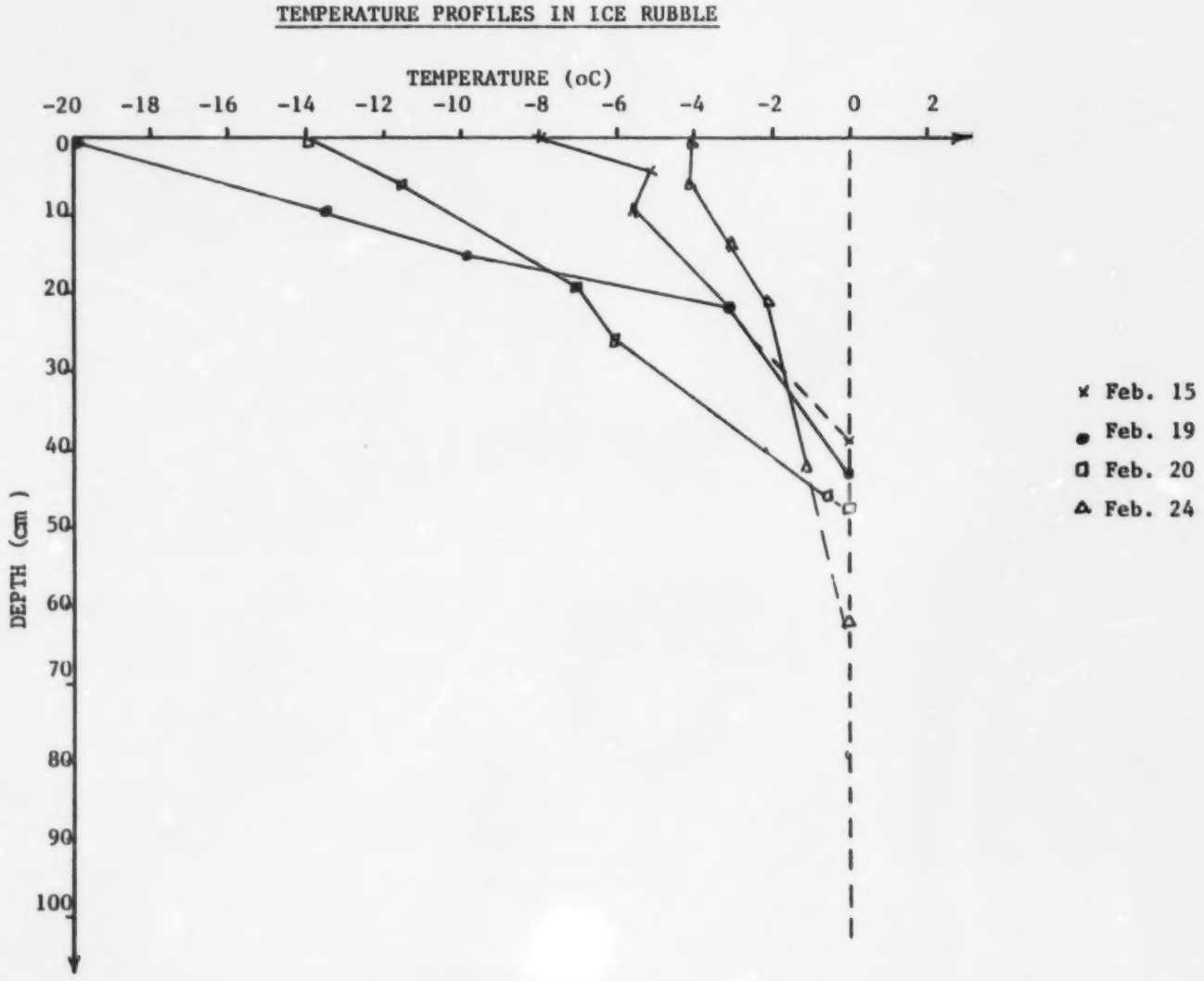

TEMPERATURE PROFILES IN ICE RUBBLE
TEMPERATURE (oC)
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
DEPTH (cm)
0
10
20
30
40
50
60
70
80
90
100
Feb. 15
Feb. 19
Feb. 20
Feb. 24

Figure 10

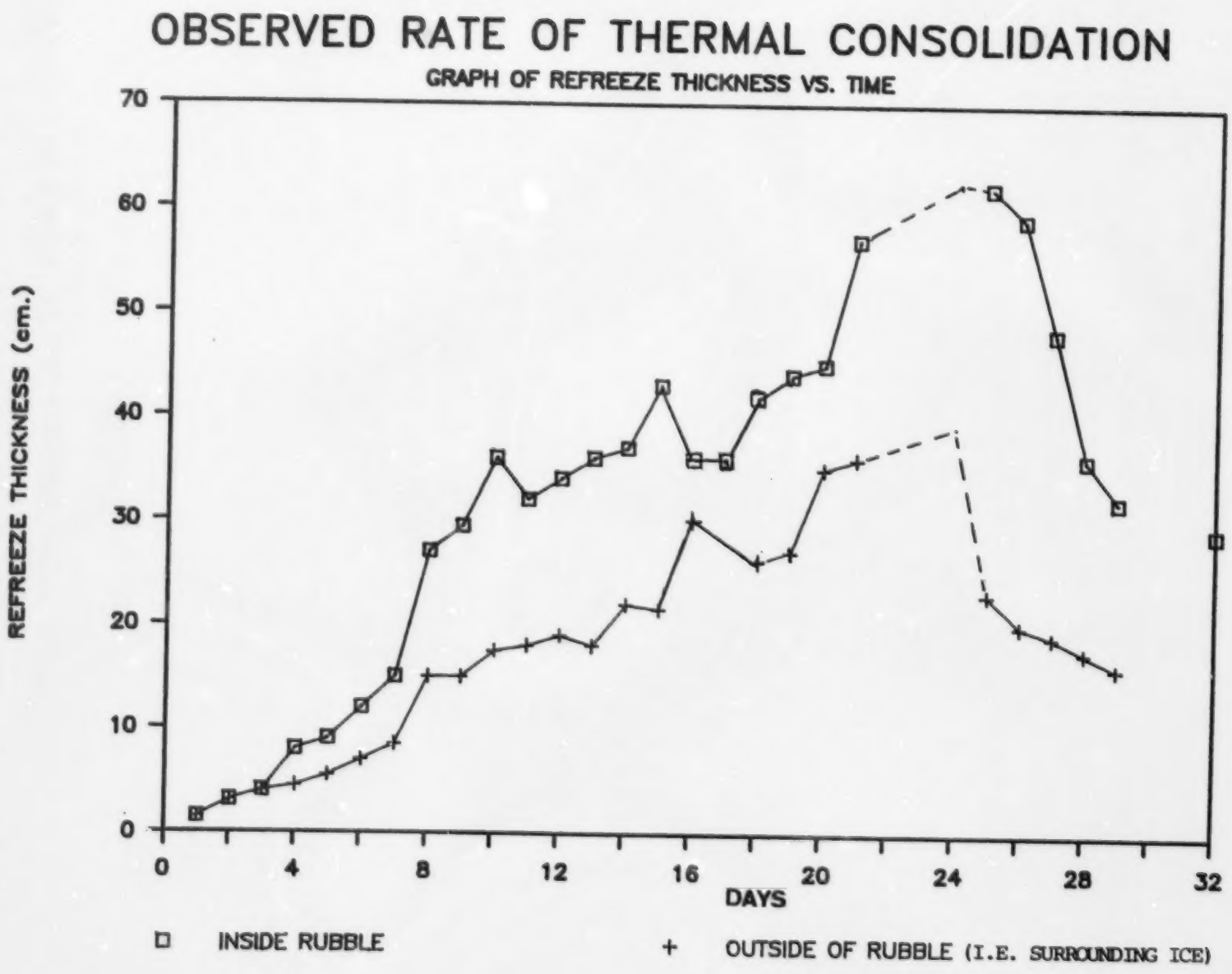

OBSERVED RATE OF THERMAL CONSOLIDATION
GRAPH OF REFREEZE THICKNESS VS. TIME
REFREEZE THICKNESS (cm.)
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
DAYS
INSIDE RUBBLE
OUTSIDE OF RUBBLE (I.E. SURROUNDING ICE)

Figure 11

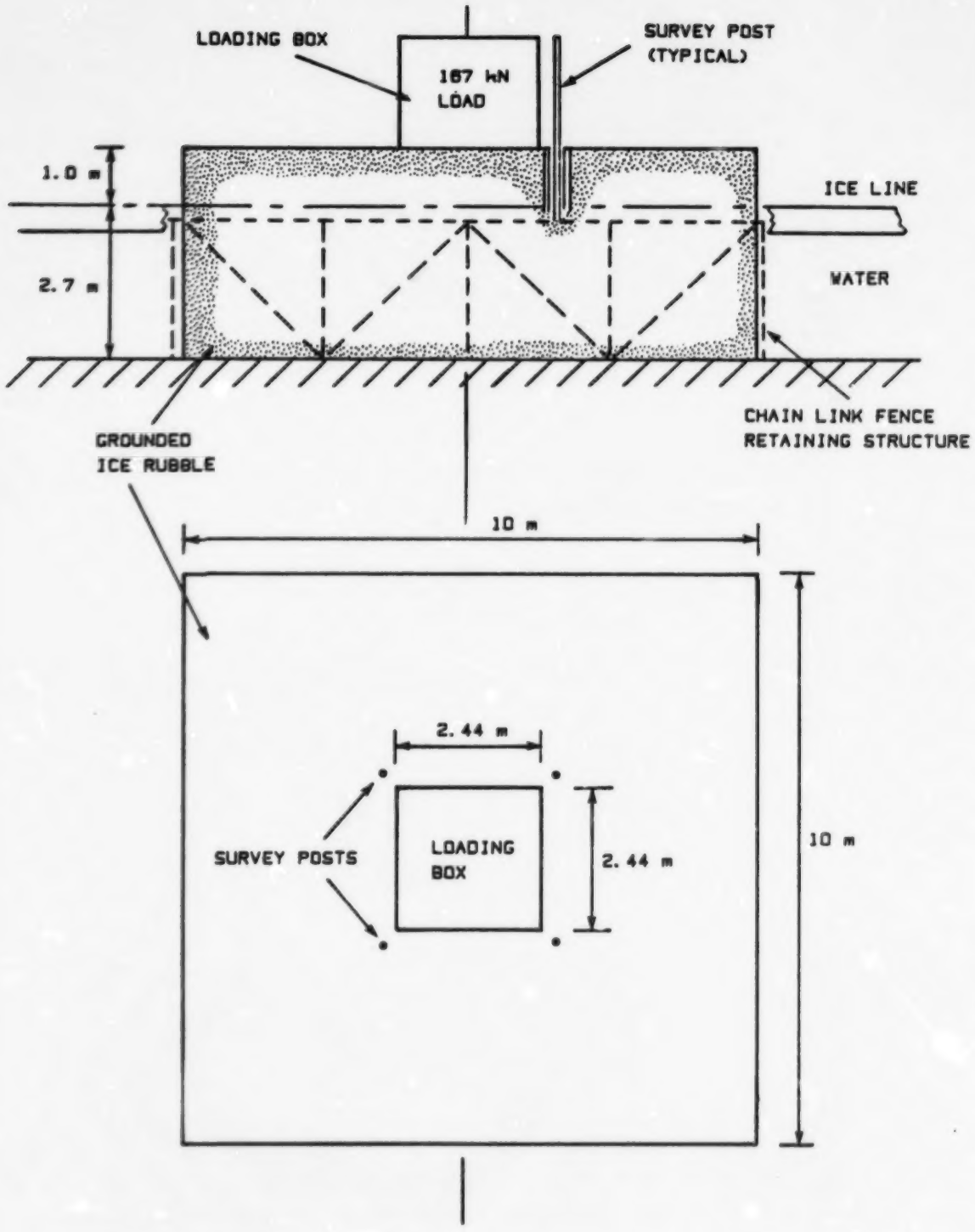
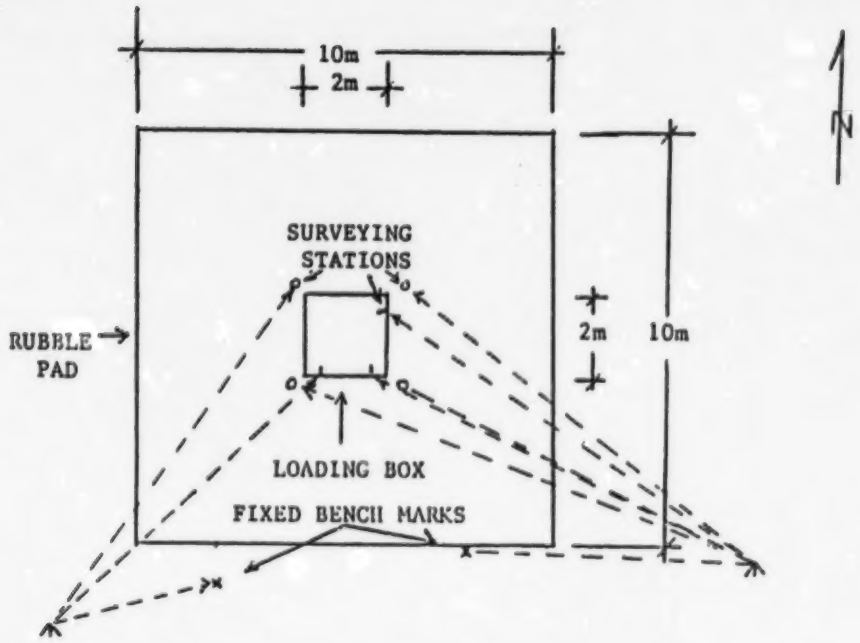
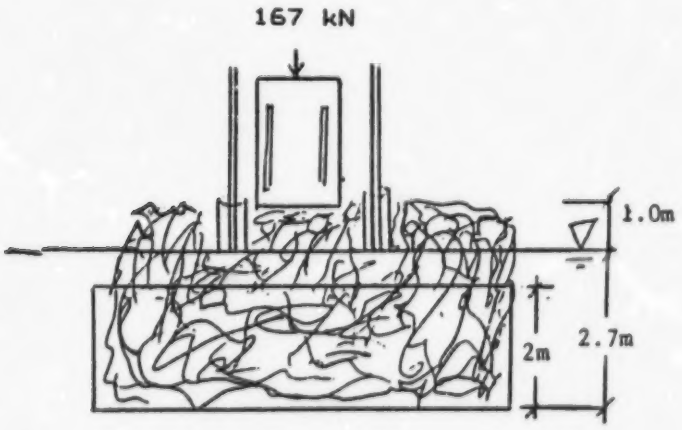


FIGURE 12 ARRANGEMENT FOR ICE RUBBLE SETTLEMENT TEST





SURVEYING LAYOUT
FOR MONITORING THE RATE OF
SETTLEMENT

Figure 13

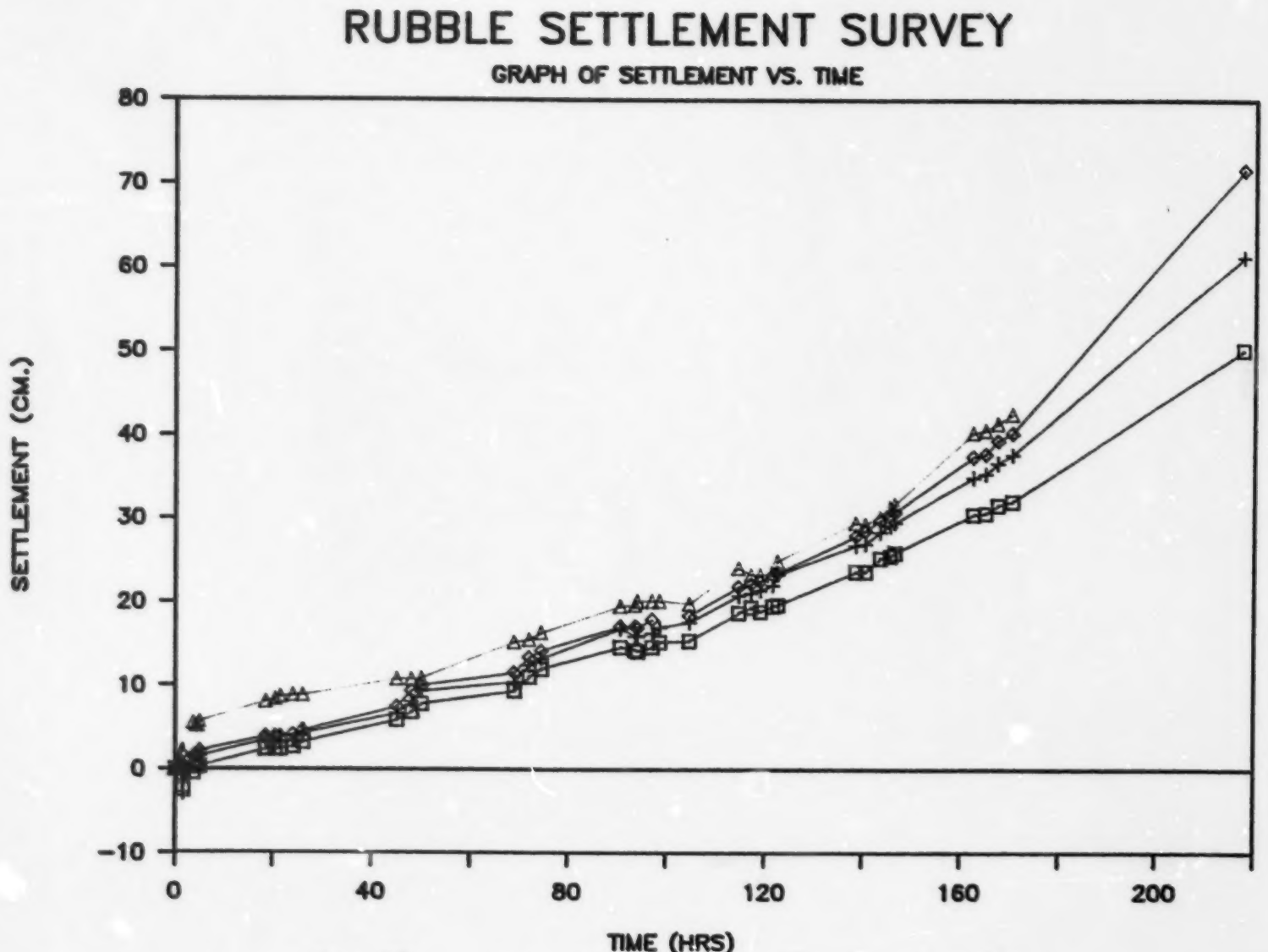

RUBBLE SETTLEMENT SURVEY
GRAPH OF SETTLEMENT VS. TIME
SETTLEMENT (CM.)
80
70
60
50
40
30
20
10
0
-10
0
40
80
120
160
200
TIME (HRS)

Figure 14

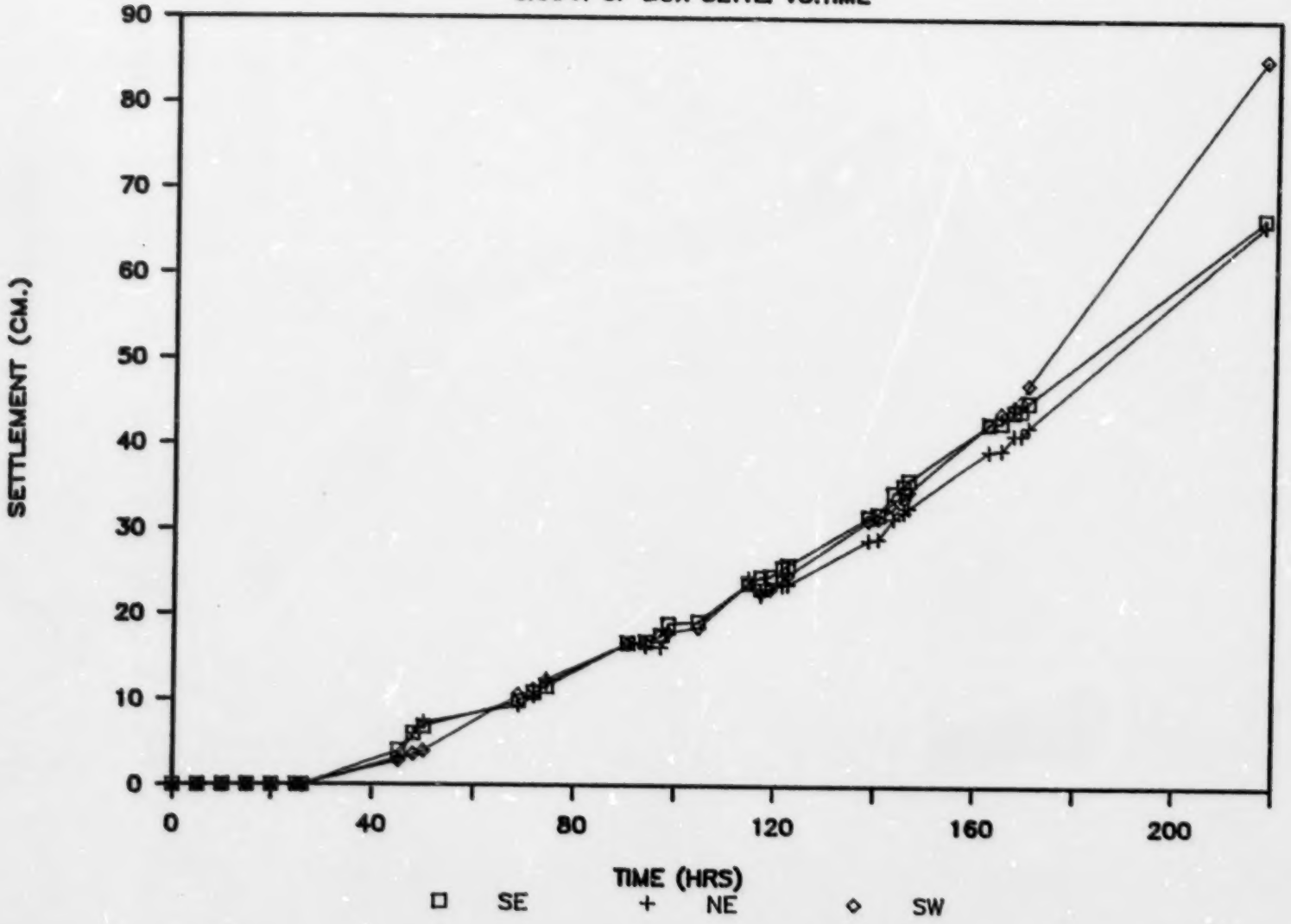

BOX SETTLEMENT SURVEY
GRAPH OF BOX SETTL. VS.TIME
SETTLEMENT (CM.)
90
80
70
60
50
40
30
20
10
0
0
40
80
120
160
200
TIME (HRS)
SE
NE
SW

Figure 15

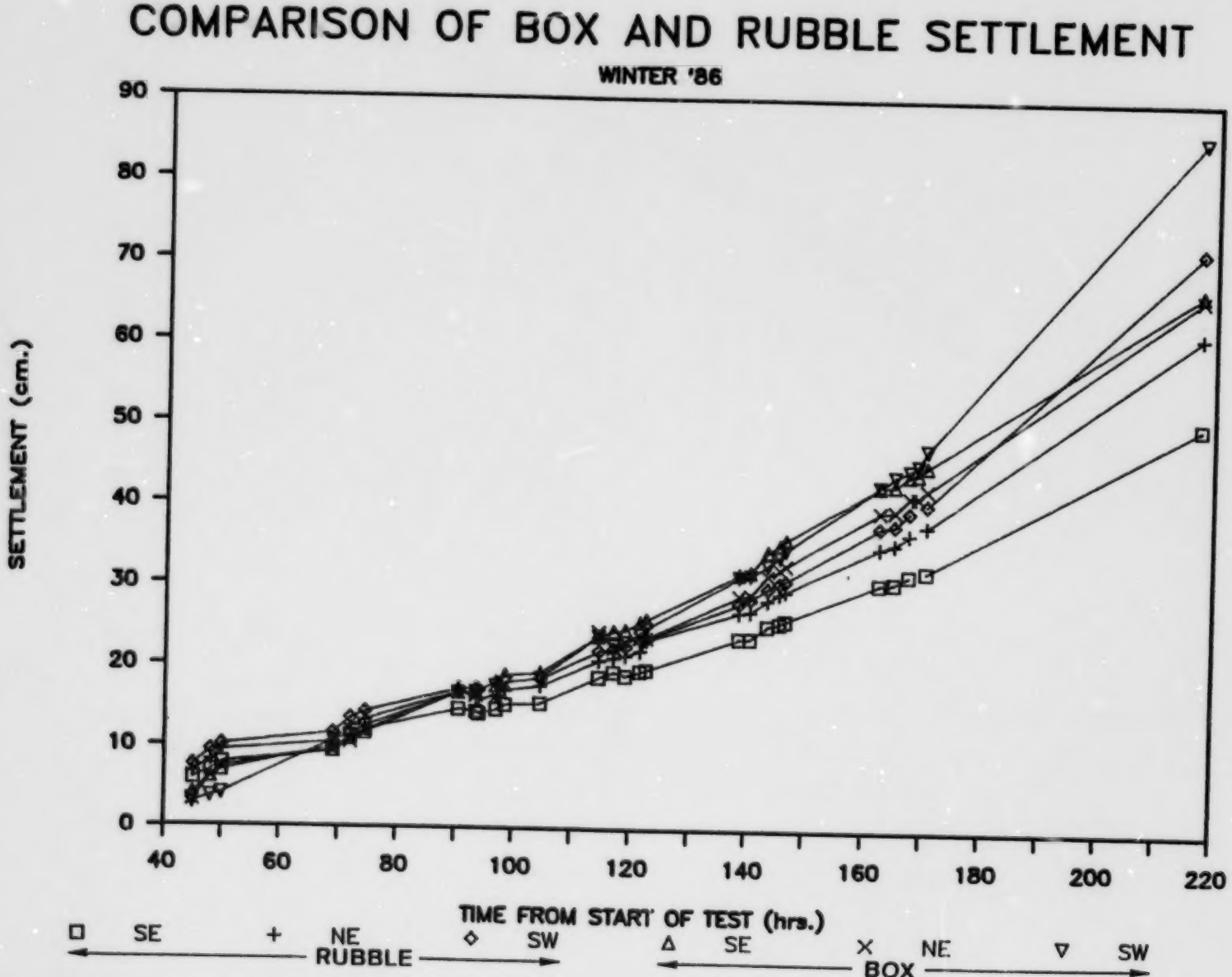

COMPARISON OF BOX AND RUBBLE SETTLEMENT
WINTER '86
SETTLEMENT (cm.)
0
10
20
30
40
50
60
70
80
90
40
60
80
100
120
140
160
180
200
220
TIME FROM START OF TEST (hrs.)
□ SE
+ NE
◇ SW
RUBBLE
Δ SE
× NE
▽ SW
BOX

Figure 16

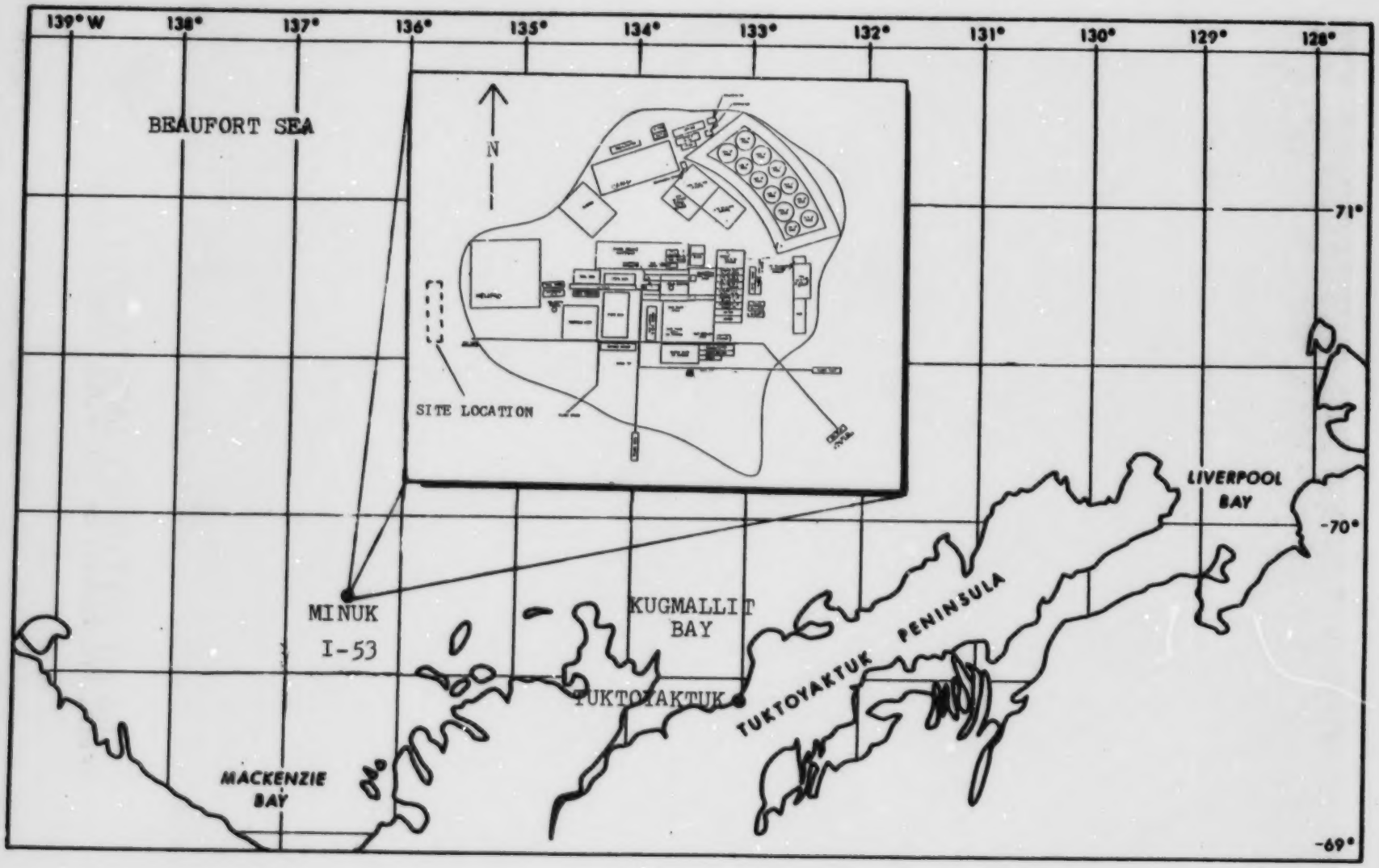
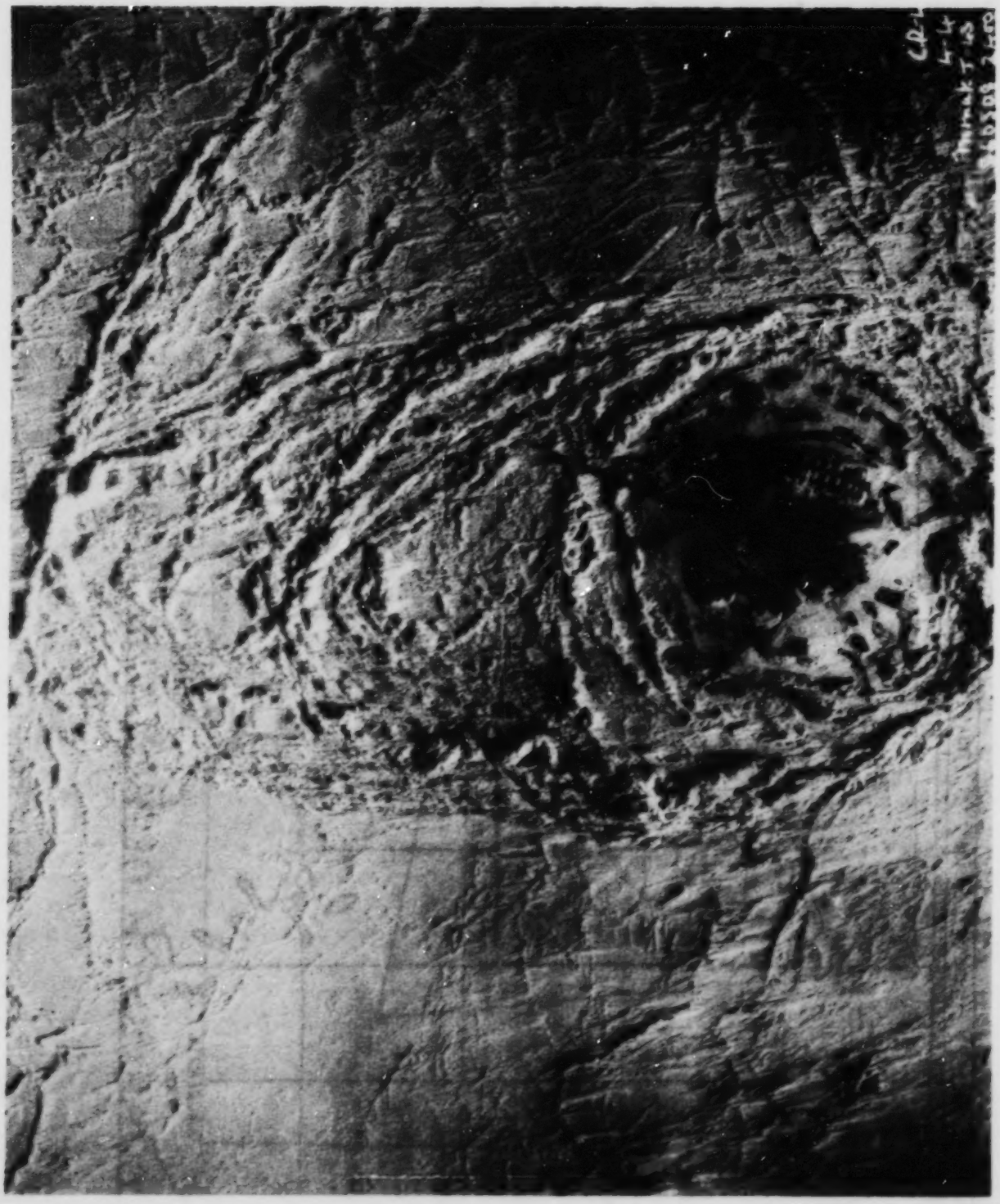
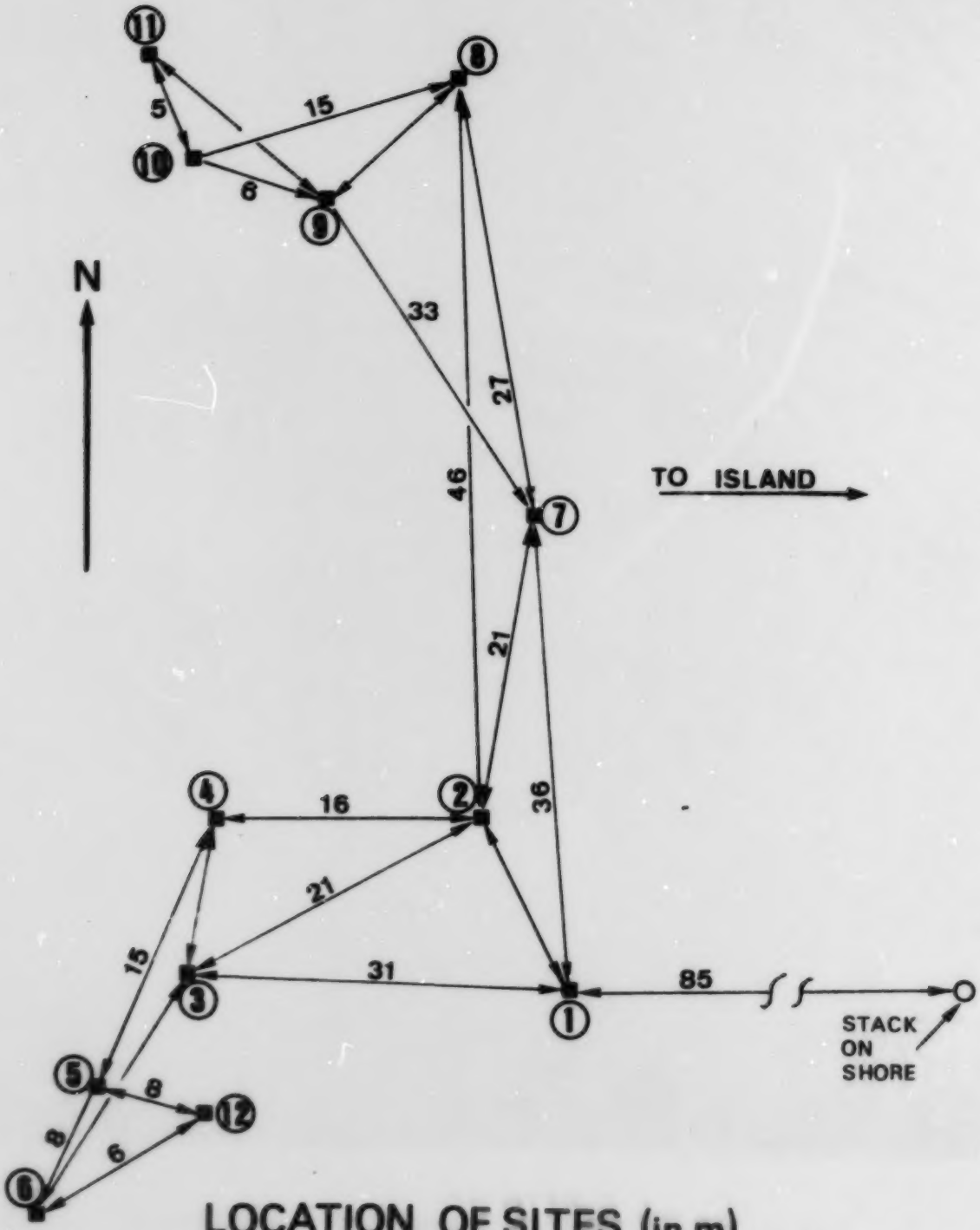


FIGURE 17 MAP SHOWING THE LOCATION OF MINUK



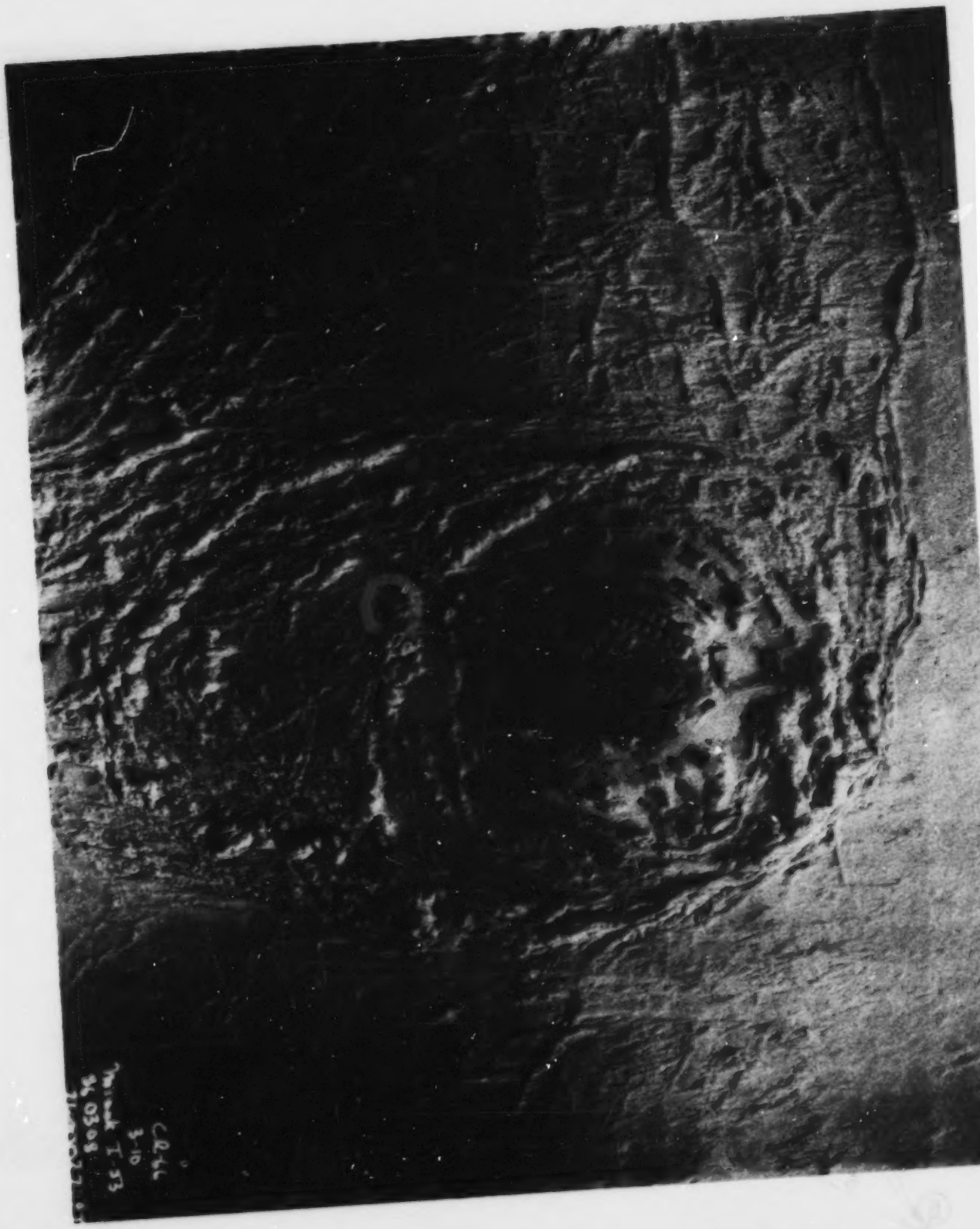
AERIAL PHOTOGRAPH OF THE MINUK RUBBLE FIELD

Figure 18



LOCATION OF SITES (in m)

Figure 19



SITE LOCATIONS MARKED ON PHOTO OF RUBBLE FIELD

Figure 20

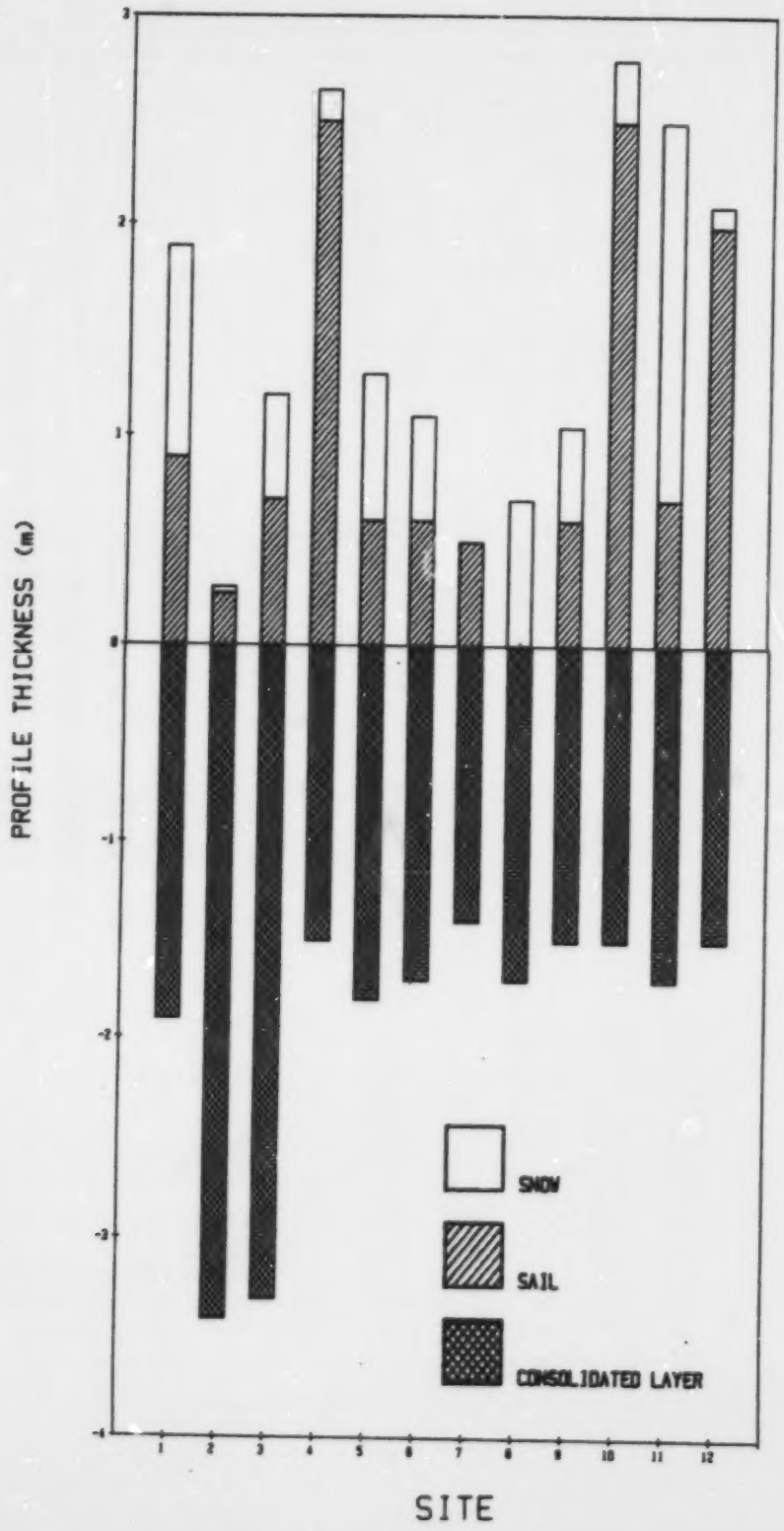


FIGURE 21 LAYER THICKNESS PROFILE THROUGH ICE RUBBLE - FIRST ARCTIC FIELD TRIP (FEBRUARY)

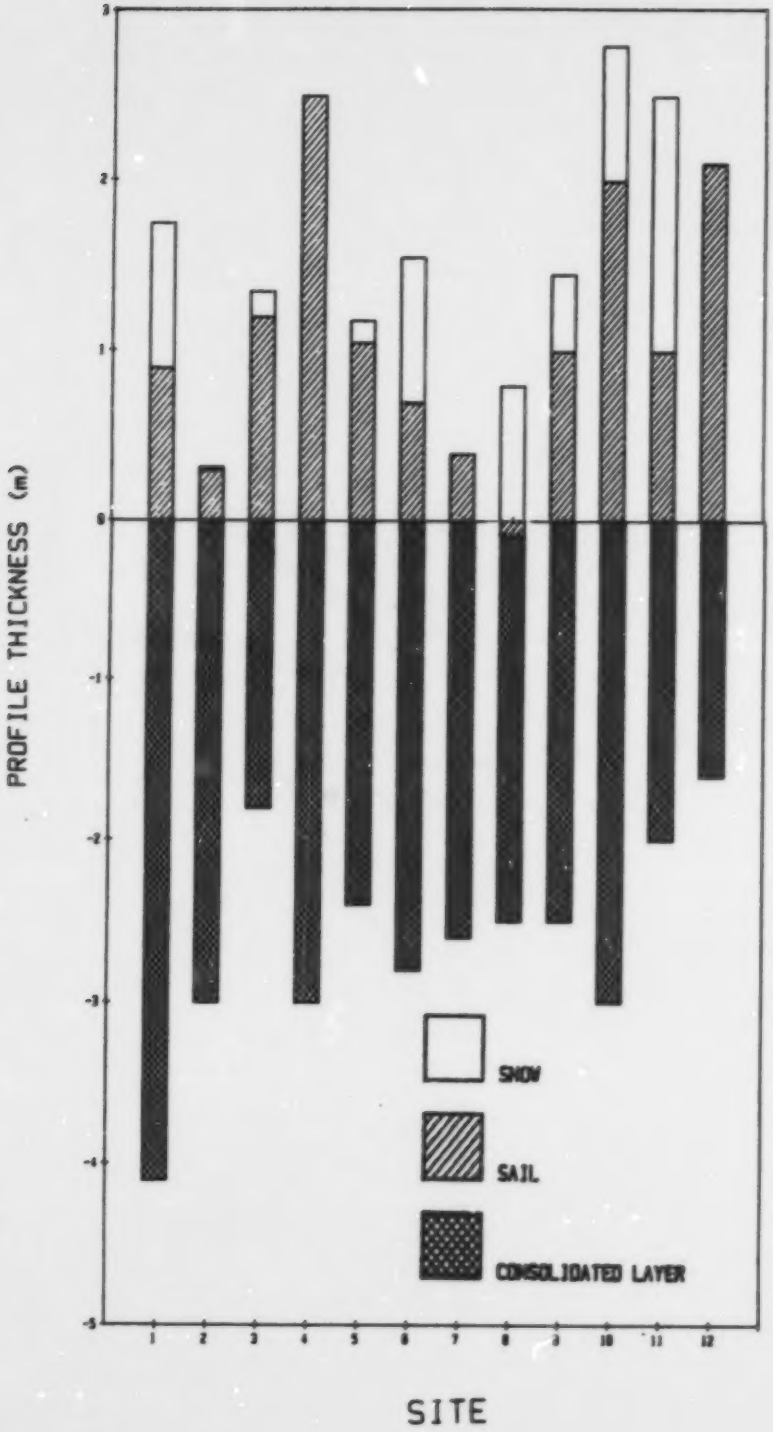


FIGURE 22 LAYER THICKNESS PROFILE THROUGH ICE RUBBLE - SECOND ARCTIC FIELD TRIP (MARCH)

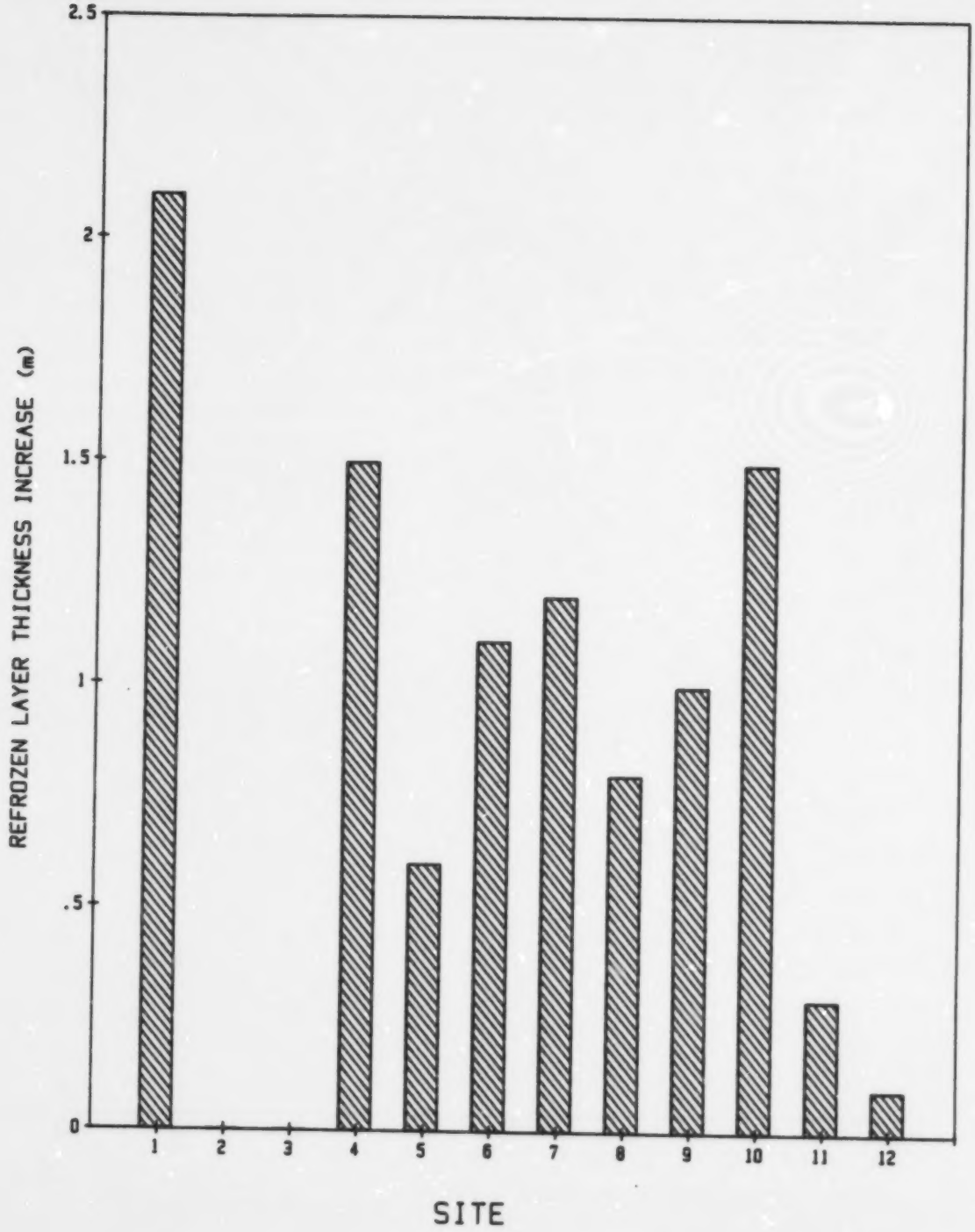


FIGURE 23 INCREASE IN REFROZEN LAYER THICKNESS FROM FIRST TO SECOND ARCTIC FIELD TRIPS

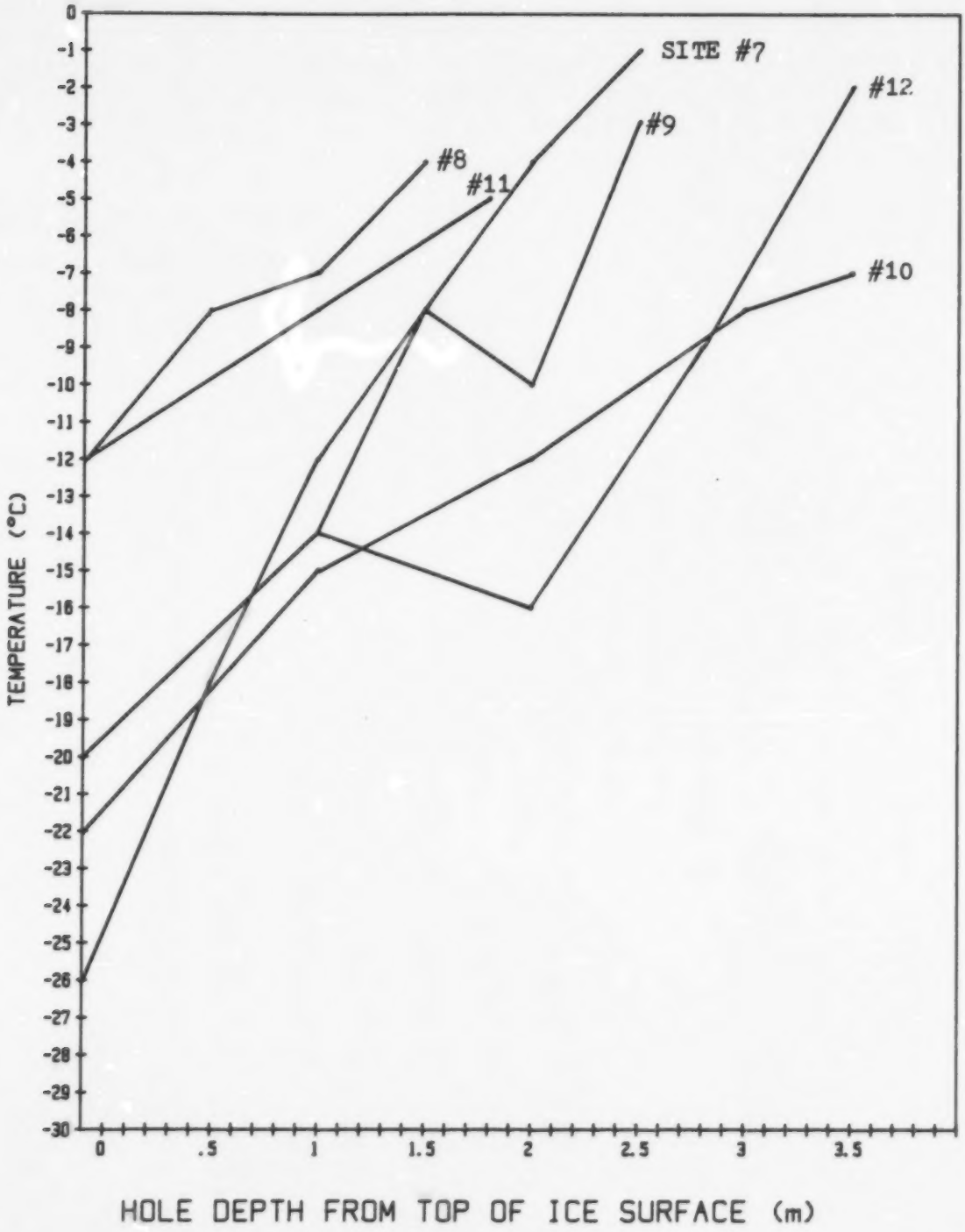


FIGURE 24 TEMPERATURE PROFILE THROUGH ICE RUBBLE - FIRST ARCTIC FIELD TRIP (FEBRUARY)

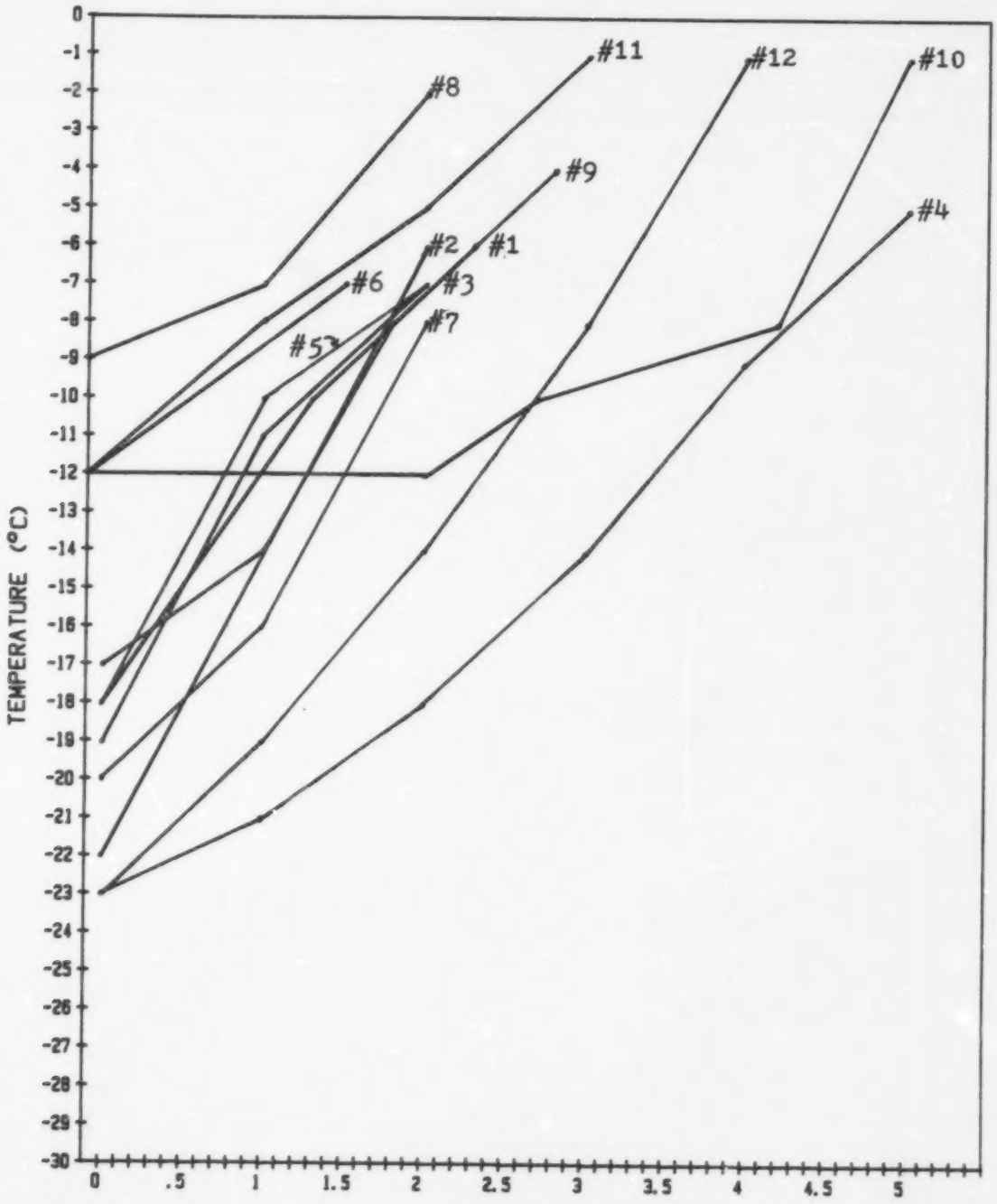


FIGURE 25 TEMPERATURE PROFILE THROUGH ICE RUBBLE - SECOND ARCTIC FIELD TRIP (MARCH)

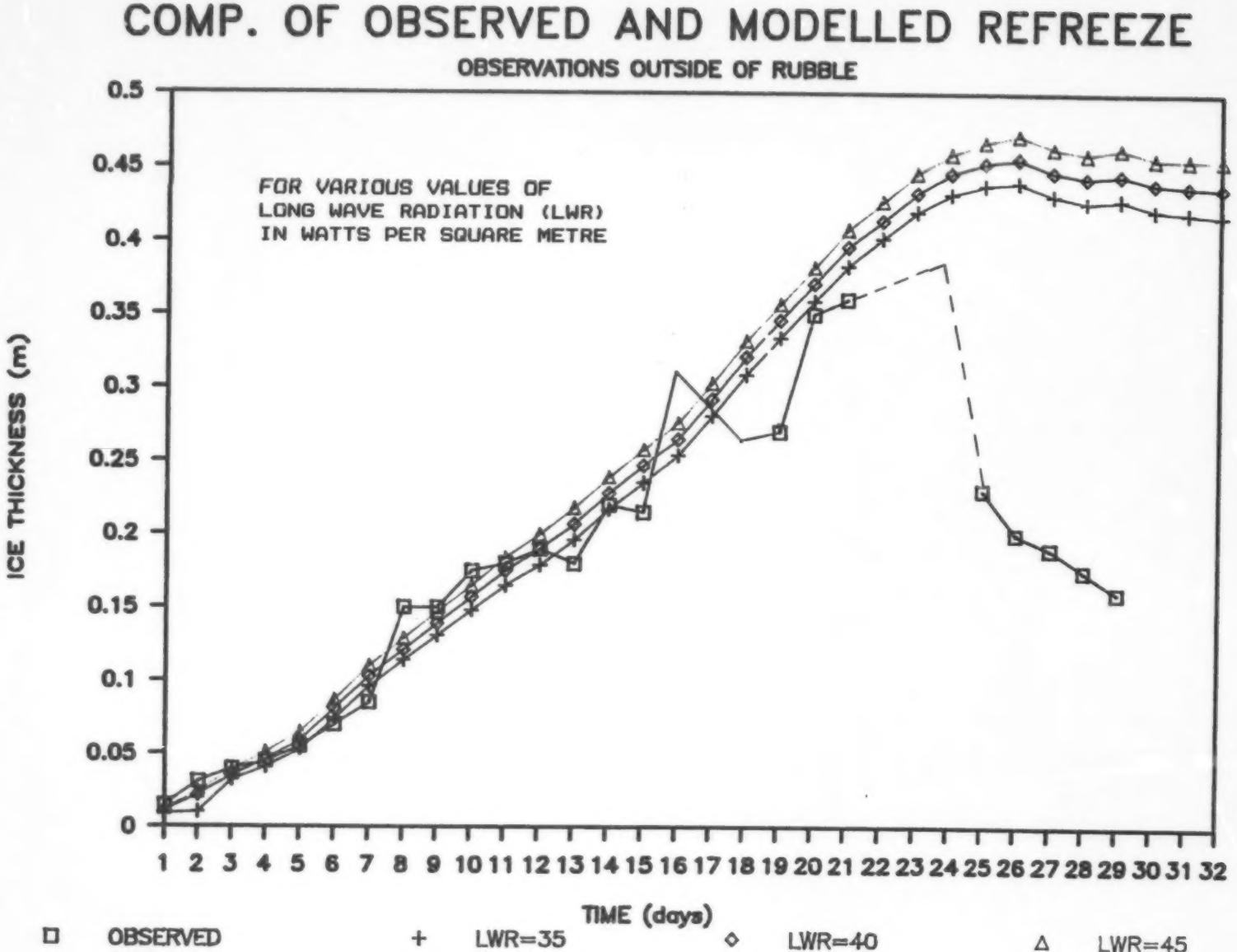

COMP. OF OBSERVED AND MODELLED REFREEZE
OBSERVATIONS OUTSIDE OF RUBBLE
FOR VARIOUS VALUES OF
LONG WAVE RADIATION (LWR)
IN WATTS PER SQUARE METRE
ICE THICKNESS (m)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
TIME (days)
OBSERVED
LWR=35
LWR=40
LWR=45

Figure 26

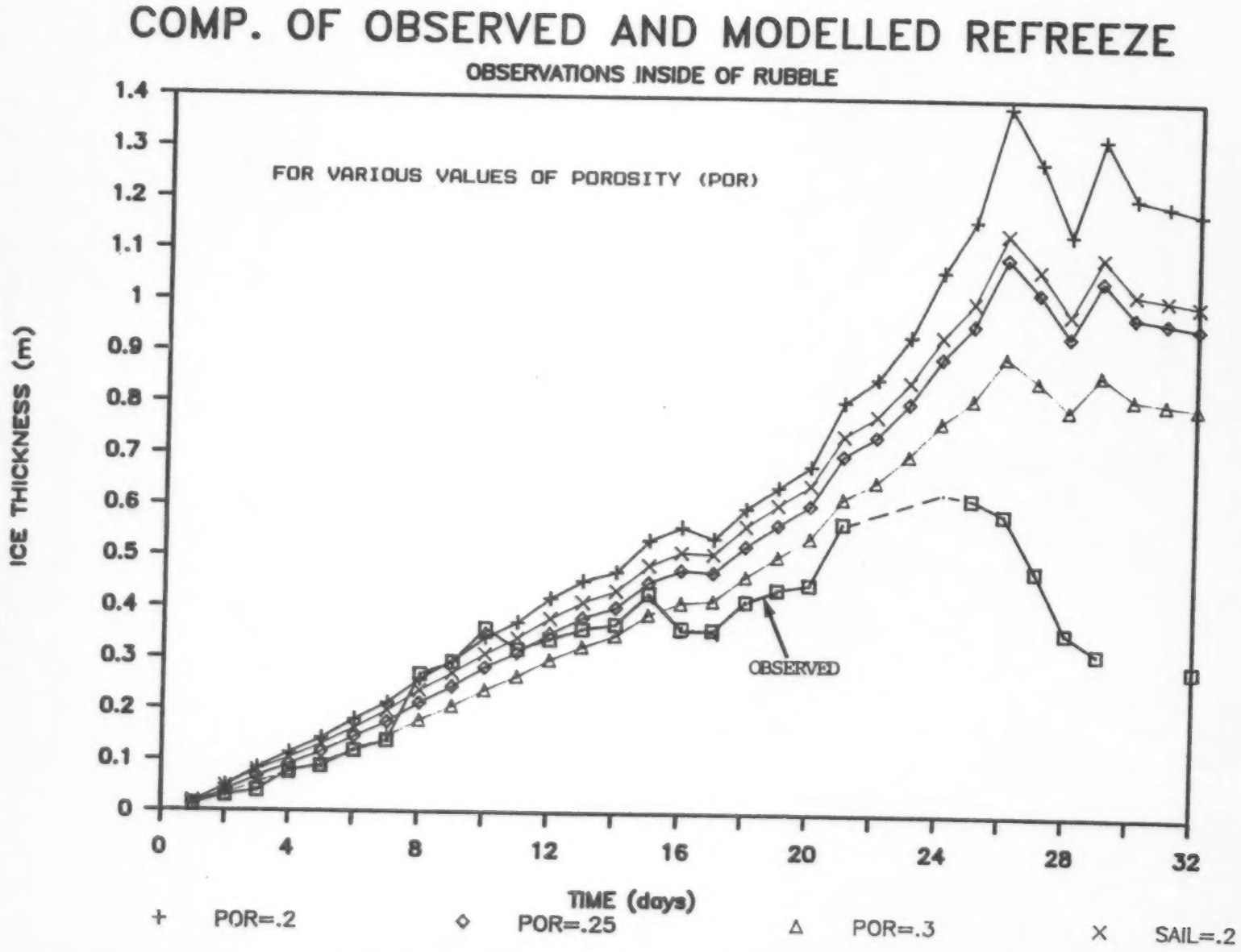

COMP. OF OBSERVED AND MODELLED REFREEZE
OBSERVATIONS INSIDE OF RUBBLE
FOR VARIOUS VALUES OF POROSITY (POR)
ICE THICKNESS (m)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
OBSERVED
0
4
8
12
16
20
24
28
32
TIME (days)
+ POR=.2
◇ POR=.25
△ POR=.3
× SAIL=.2

Figure 27

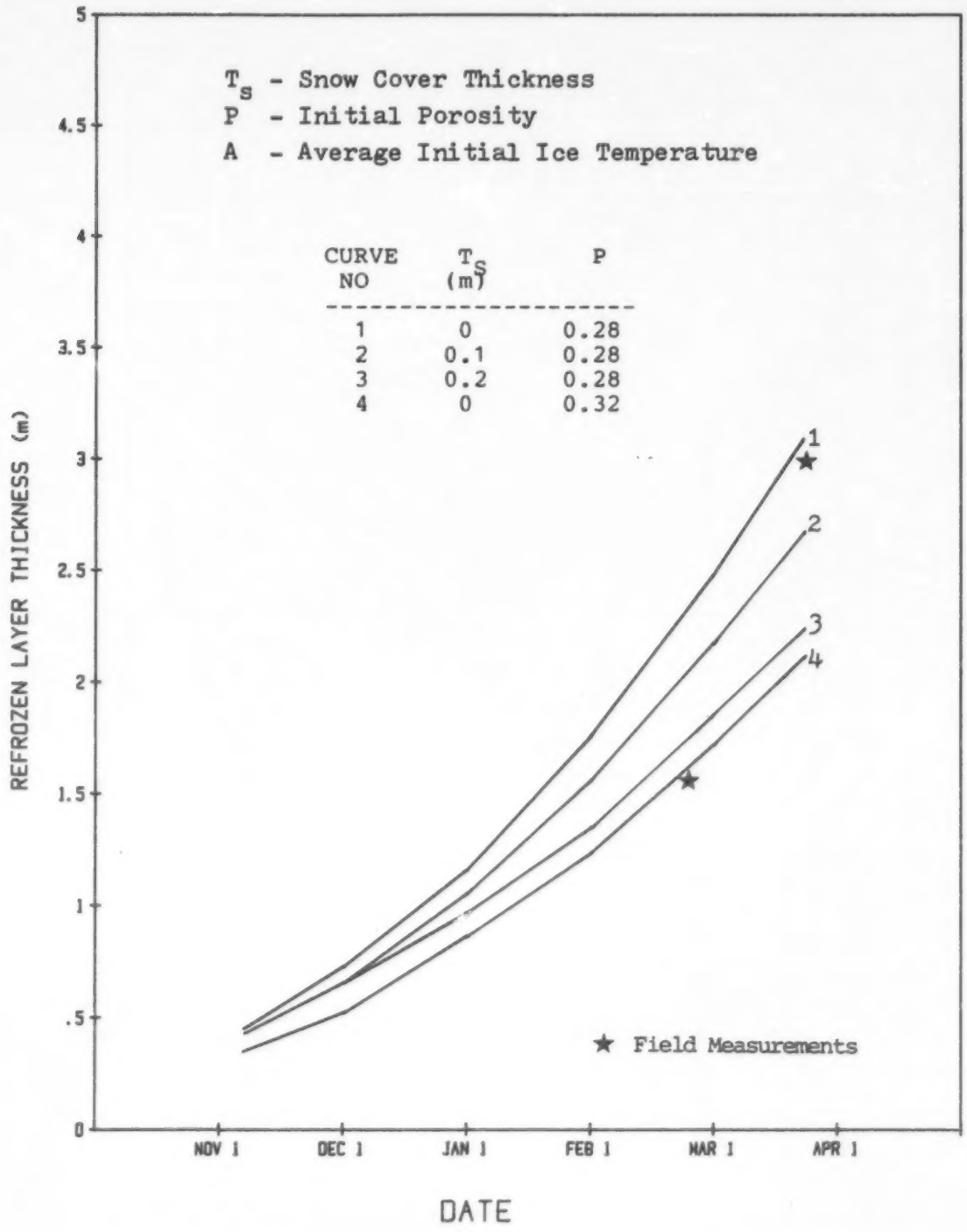


FIGURE 28 COMPARISON OF ICEGROW PARAMETRIC ANALYSIS WITH MINUK FIELD DATA - SITE 4

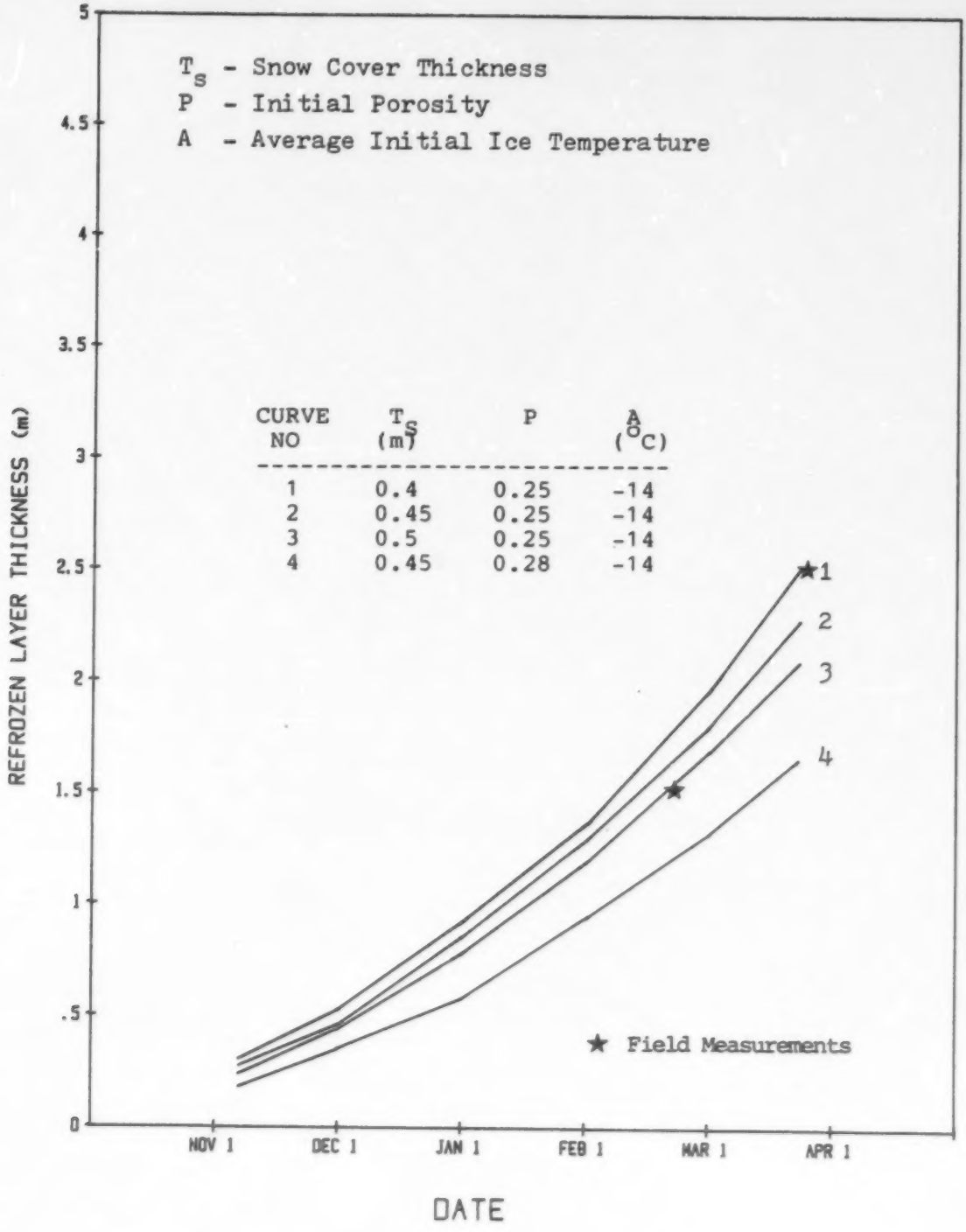


FIGURE 29 COMPARISON OF ICEGROW OUTPUT WITH MINUK FIELD DATA - SITE 9

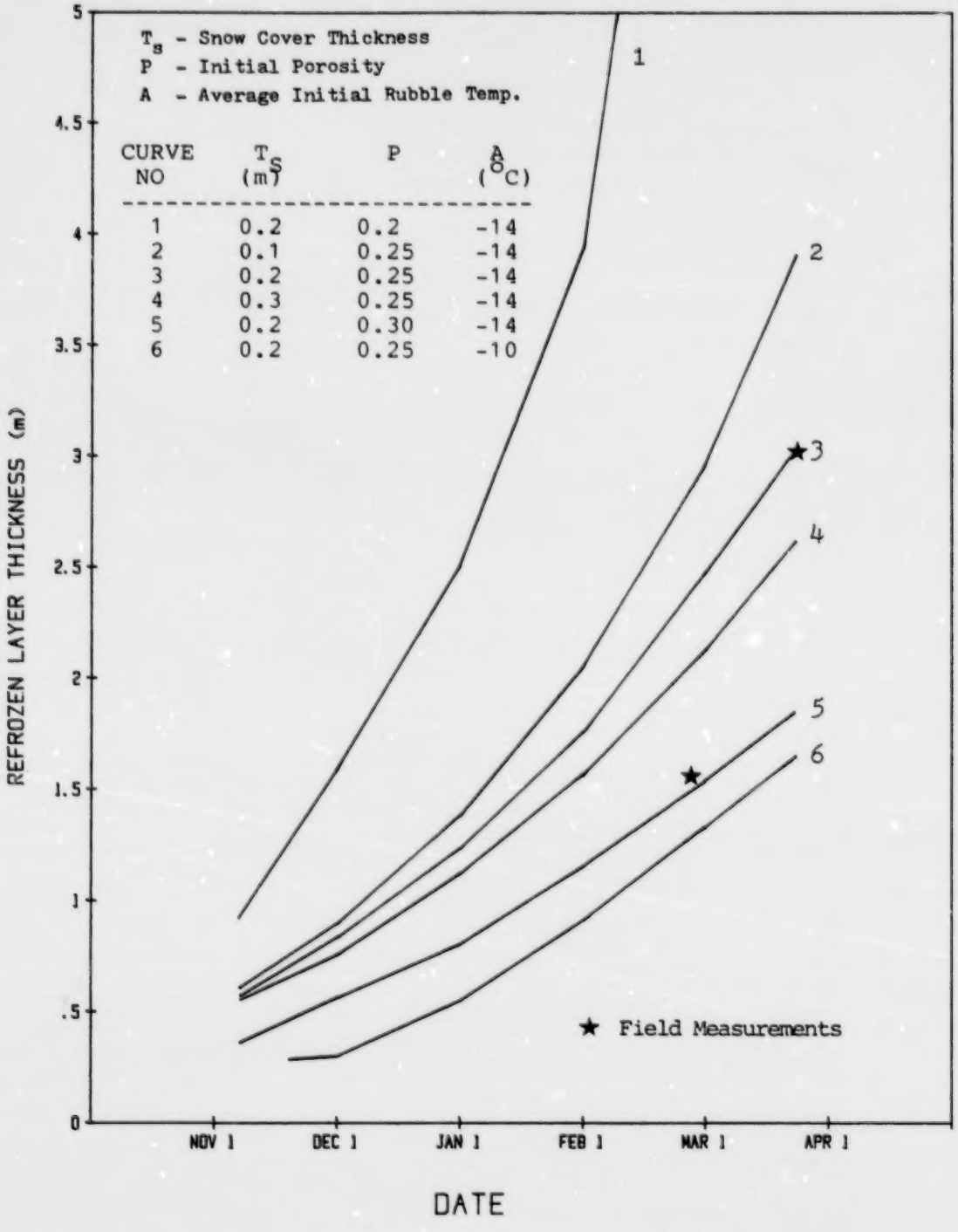
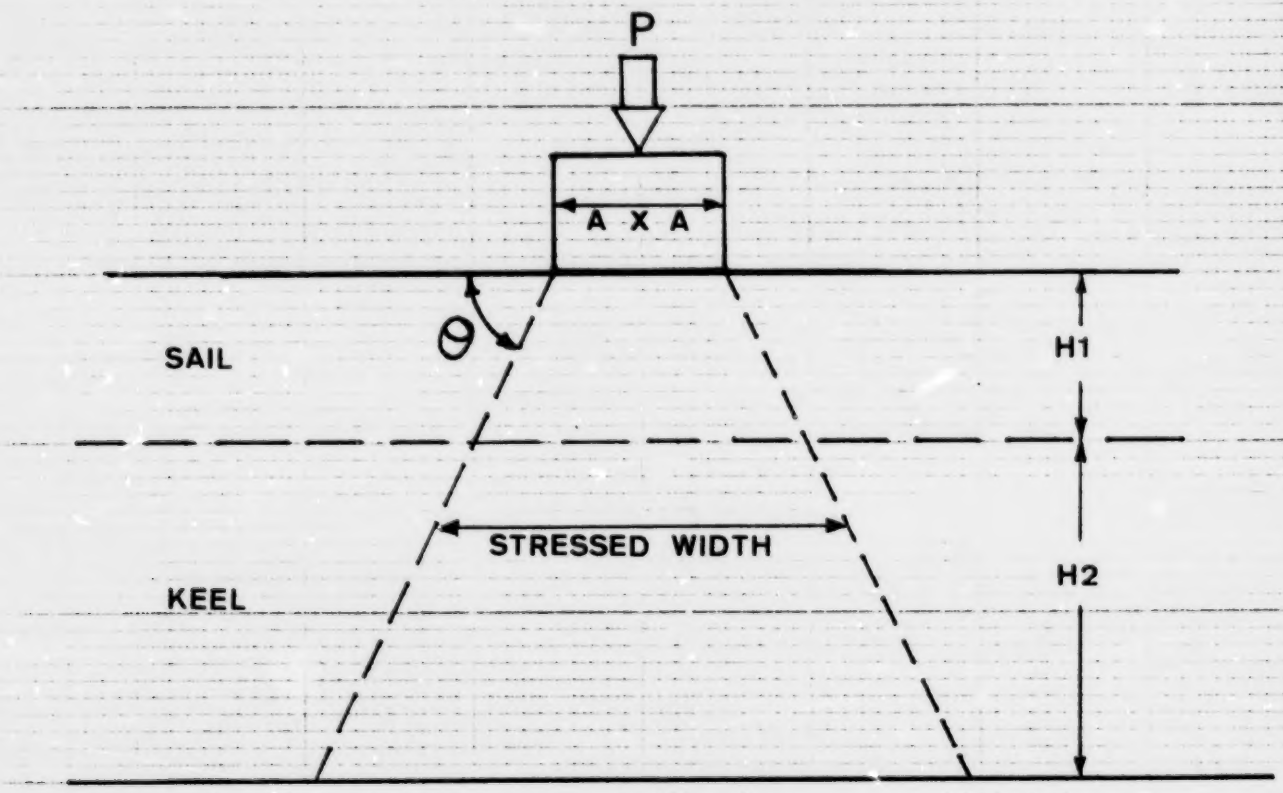
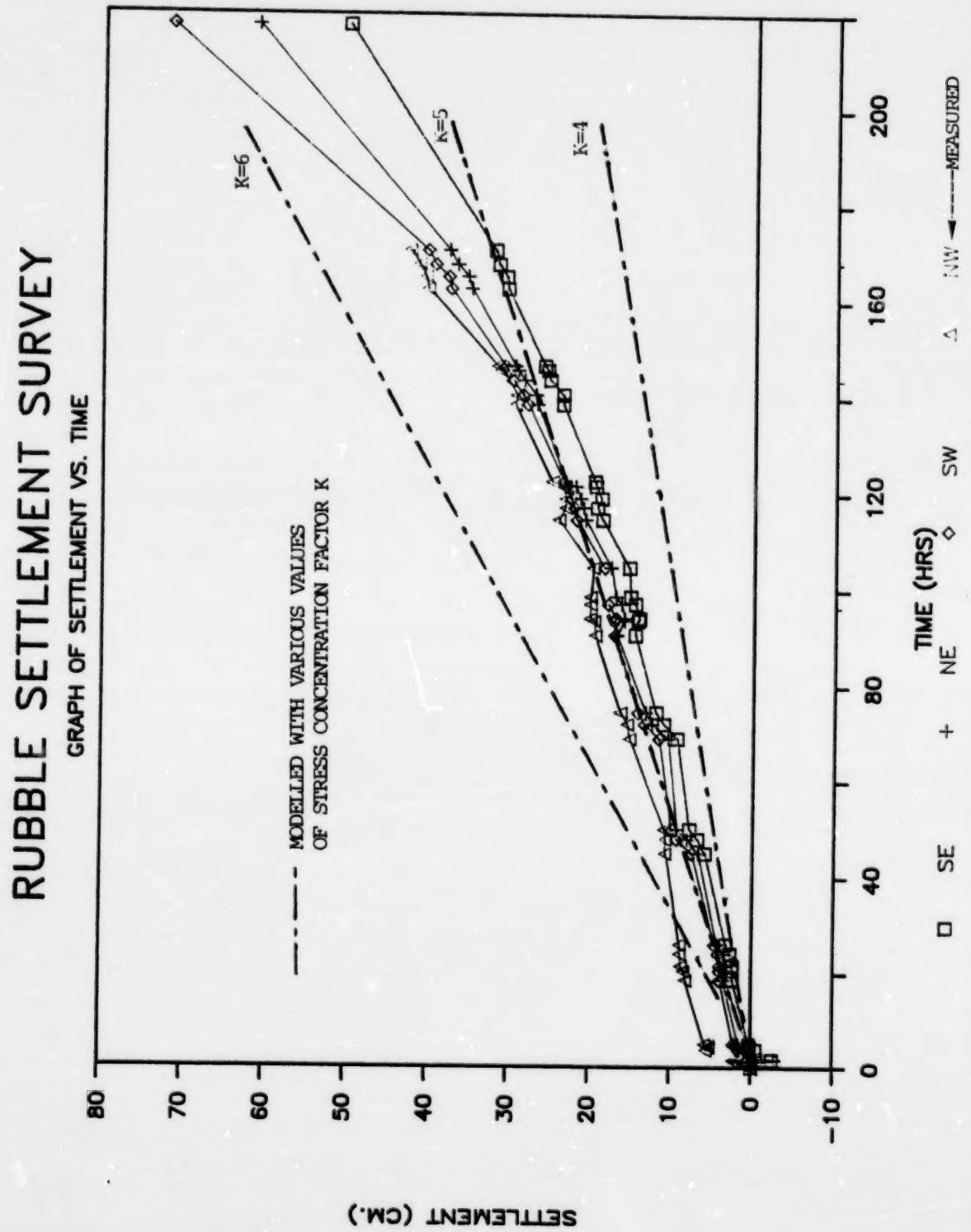


FIGURE 30 COMPARISON OF ICEGROW PARAMETRIC ANALYSIS WITH MINUK FIELD DATA - SITE 10



CONFIGURATION OF CREEP MODEL

Figure 31



COMPARISON OF MEASURED SETTLEMENT OF RUBBLE KEEL TO ANALYTICAL MODEL RESULTS

Figure 32

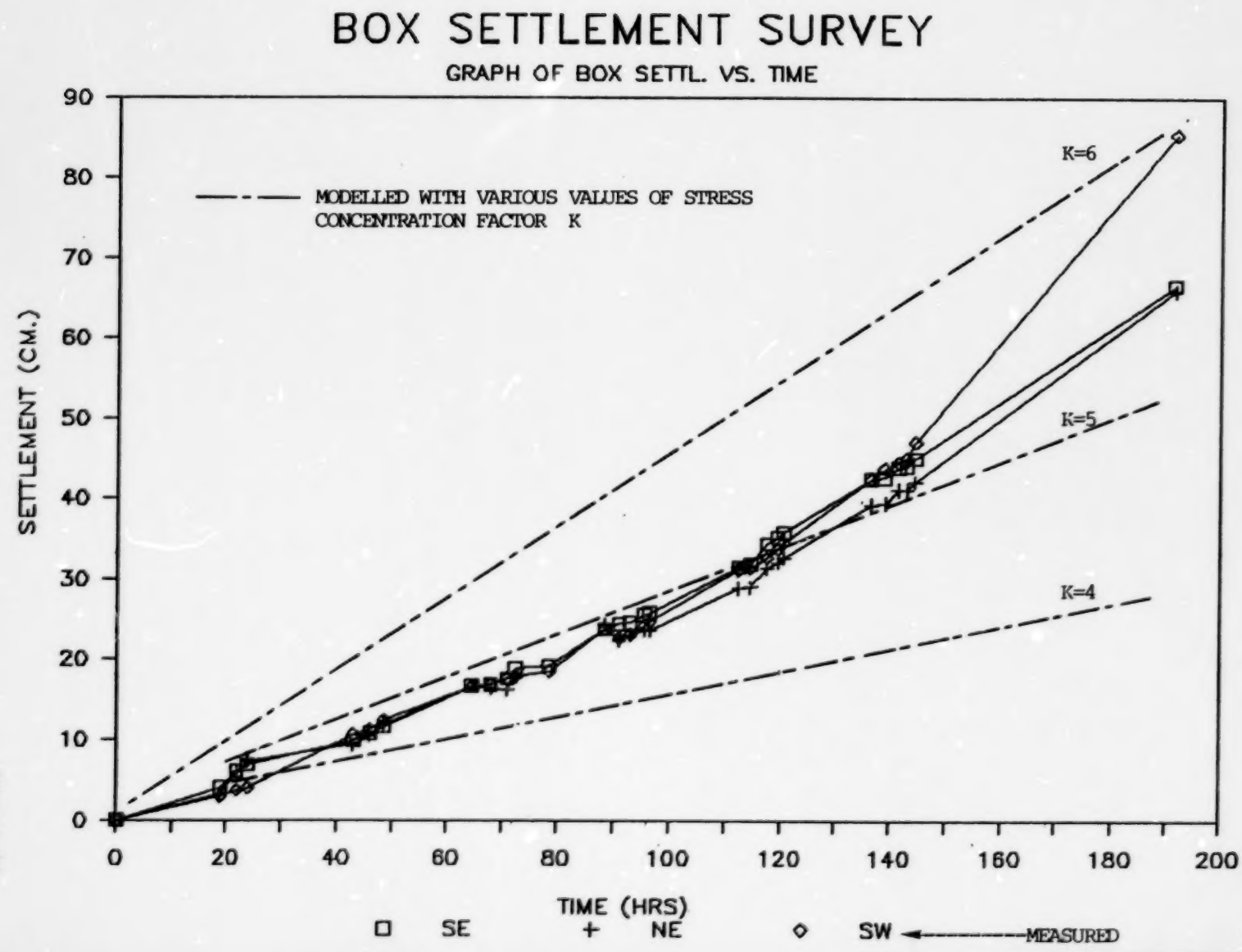


Figure 33 COMPARISON OF MEASURED SETTLEMENT OF RUBBLE TOTAL THICKNESS TO ANALYTICAL MODEL RESULTS

APPENDIX A

INPUT & OUTPUT FOR PROGRAM "ICEGROW"

- VARIATION OF LONG WAVE RADIATION RUNS FOR FREEZING OF SHEET ICE IN TEST BASIN

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	35.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.00	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	1.00	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

New porosity due to interblock freezing = 1.000

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	35.00	.000	.009	.010	3982.	.6180	.000	.000	1.4119	.01	-.07
2 FEB 1	-.80	1.00	35.00	.000	.019	.005	4367.	.5782	.000	.000	1.5007	.01	-.17
3 FEB 2	-3.20	2.00	35.00	.000	.032	.003	4618.	.7175	.000	.000	1.5589	.01	-.36
4 FEB 3	-.60	2.20	35.00	.000	.041	.003	4613.	.7166	.000	.000	1.5575	.01	-.35
5 FEB 4	-4.00	1.20	35.00	.000	.053	.002	4735.	.7357	.000	.000	1.5858	.01	-.56
6 FEB 5	-5.90	6.10	35.00	.000	.074	.001	4918.	.7644	.001	.001	1.6281	.01	-1.41
7 FEB 6	-10.50	3.00	35.00	.000	.096	.001	4962.	.7711	.001	.001	1.6381	.01	-1.90
8 FEB 7	-8.40	2.50	35.00	.000	.114	.001	4951.	.7694	.002	.002	1.6356	.01	-1.75
9 FEB 8	-10.90	1.80	35.00	.000	.131	.001	4970.	.7724	.002	.002	1.6400	.01	-2.02
10 FEB 9	-9.30	2.50	35.00	.000	.148	.000	4984.	.7746	.003	.003	1.6432	.01	-2.26
11 FEB 10	-12.20	1.90	35.00	.000	.165	.000	5002.	.7774	.004	.004	1.6474	.01	-2.63
12 FEB 11	-9.20	1.50	35.00	.000	.179	.000	4984.	.7745	.004	.005	1.6431	.01	-2.25
13 FEB 12	-10.90	3.20	35.00	.000	.196	.000	5024.	.7808	.005	.005	1.6525	.01	-3.24
14 FEB 13	-16.30	2.90	35.00	.000	.217	.000	5053.	.7854	.007	.007	1.6592	.01	-4.47
15 FEB 14	-11.40	2.80	35.00	.000	.235	.000	5034.	.7824	.008	.008	1.6547	.01	-3.59
16 FEB 15	-13.50	3.70	35.00	.000	.254	.000	5054.	.7856	.009	.009	1.6595	.01	-4.52
17 FEB 16	-28.00	3.60	35.00	.000	.281	.000	5099.	.7925	.011	.011	1.6697	.01	-8.55
18 FEB 17	-28.20	2.40	35.00	.000	.309	.000	5093.	.7917	.014	.014	1.6685	.01	-7.85
19 FEB 18	-32.70	1.50	35.00	.000	.334	.000	5092.	.7915	.016	.016	1.6682	.01	-7.72
20 FEB 19	-34.20	2.00	35.00	.000	.359	.000	5103.	.7932	.018	.019	1.6708	.01	-8.33
21 FEB 20	-20.30	2.50	35.00	.000	.383	.000	5085.	.7904	.021	.021	1.6665	.01	-6.83
22 FEB 21	-19.50	3.60	35.00	.000	.402	.000	5090.	.7911	.023	.023	1.6676	.01	-7.15
23 FEB 22	-12.00	1.80	35.00	.000	.420	.000	5058.	.7861	.025	.025	1.6603	.01	-4.73
24 FEB 23	-2.50	2.30	35.00	.000	.432	.000	4992.	.7759	.026	.027	1.6452	.01	-2.48
25 FEB 24	3.20	2.80	35.00	.000	.438	.002	4776.	.7421	.025	.026	1.5952	.01	-.98
26 FEB 25	11.30	7.10	35.00	.000	.440	.000	5032.	.7820	.027	.028	1.6542	.01	3.06
27 FEB 26	9.20	4.00	35.00	.000	.431	.001	4948.	.7689	.025	.026	1.6348	.01	1.77
28 FEB 27	6.50	1.70	35.00	.000	.426	.002	4741.	.7366	.023	.025	1.5871	.01	-.87
29 FEB 28	12.20	3.80	35.00	.000	.428	.000	5000.	.7770	.025	.026	1.6468	.01	2.34
30 MAR 1	8.00	3.00	35.00	.000	.421	.001	4814.	.7480	.023	.024	1.6039	.01	.36
31 MAR 2	9.20	2.30	35.00	.000	.419	.002	4753.	.7386	.022	.024	1.5900	.01	.61
32 MAR 3	8.00	2.40	35.00	.000	.417	.003	4626.	.7187	.021	.023	1.5606	.01	.41

Degree-day thickness= .458

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	40.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.00	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	1.00	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

New porosity due to interblock freezing = 1.000

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	40.00	.000	.011	.009	4109.	.6380	.000	.000	1.4413	.01	-.10
2 FEB 1	-.80	1.00	40.00	.000	.022	.004	4457.	.6923	.000	.000	1.5217	.01	-.22
3 FEB 2	-3.20	2.00	40.00	.000	.035	.002	4674.	.7262	.000	.000	1.5717	.01	-.44
4 FEB 3	-.60	2.20	40.00	.000	.046	.002	4675.	.7263	.000	.000	1.5719	.01	-.44
5 FEB 4	-4.00	1.20	40.00	.000	.059	.002	4782.	.7430	.000	.000	1.5966	.01	-.68
6 FEB 5	-5.90	6.10	40.00	.000	.081	.001	4933.	.7666	.001	.001	1.6315	.01	-1.55
7 FEB 6	-10.50	3.00	40.00	.000	.103	.001	4975.	.7731	.001	.001	1.6411	.01	-2.09
8 FEB 7	-8.40	2.50	40.00	.000	.121	.001	4965.	.7717	.002	.002	1.6390	.01	-1.95
9 FEB 8	-10.90	1.80	40.00	.000	.139	.000	4984.	.7746	.003	.003	1.6432	.01	-2.26
10 FEB 9	-9.30	2.50	40.00	.000	.157	.000	4995.	.7764	.003	.003	1.6458	.01	-2.46
11 FEB 10	-12.20	1.90	40.00	.000	.175	.000	5013.	.7790	.004	.004	1.6498	.01	-2.90
12 FEB 11	-9.20	1.50	40.00	.000	.190	.000	4997.	.7766	.005	.005	1.6463	.01	-2.53
13 FEB 12	-10.90	3.20	40.00	.000	.207	.000	5031.	.7820	.006	.006	1.6541	.01	-3.49
14 FEB 13	-16.30	2.90	40.00	.000	.228	.000	5059.	.7862	.007	.007	1.6604	.01	-4.76
15 FEB 14	-11.40	2.80	40.00	.000	.247	.000	5041.	.7834	.009	.009	1.6563	.01	-3.86
16 FEB 15	-13.50	3.70	40.00	.000	.265	.000	5059.	.7863	.010	.010	1.6605	.01	-4.78
17 FEB 16	-28.00	3.60	40.00	.000	.292	.000	5101.	.7928	.012	.012	1.6701	.01	-8.88
18 FEB 17	-28.20	2.40	40.00	.000	.321	.000	5096.	.7921	.015	.015	1.6691	.01	-8.21
19 FEB 18	-32.70	1.50	40.00	.000	.346	.000	5096.	.7920	.017	.017	1.6690	.01	-8.16
20 FEB 19	-34.20	2.00	40.00	.000	.371	.000	5106.	.7936	.020	.020	1.6713	.01	-9.75
21 FEB 20	-20.30	2.50	40.00	.000	.396	.000	5088.	.7908	.022	.023	1.6672	.01	-7.19
22 FEB 21	-19.50	3.60	40.00	.000	.414	.000	5092.	.7914	.024	.025	1.6681	.01	-7.63
23 FEB 22	-12.00	1.80	40.00	.000	.433	.000	5064.	.7870	.027	.027	1.6616	.01	-5.08
24 FEB 23	-2.50	2.30	40.00	.000	.446	.000	5005.	.7779	.028	.028	1.6481	.01	-2.71
25 FEB 24	3.20	2.80	40.00	.000	.453	.001	4840.	.7521	.027	.028	1.6101	.01	-.90
26 FEB 25	11.30	7.10	40.00	.000	.456	.000	5029.	.7816	.029	.030	1.6536	.01	3.46
27 FEB 26	9.20	4.00	40.00	.000	.447	.001	4933.	.7667	.027	.028	1.6316	.01	1.61
28 FEB 27	6.50	1.70	40.00	.000	.443	.001	4835.	.7512	.026	.027	1.6087	.01	-.88
29 FEB 28	12.20	3.80	40.00	.000	.445	.000	4993.	.7759	.028	.028	1.6452	.01	2.49
30 MAR 1	8.00	3.00	40.00	.000	.439	.002	4748.	.7377	.025	.026	1.5887	.01	.64
31 MAR 2	9.20	2.30	40.00	.000	.437	.003	4621.	.7179	.023	.025	1.5594	.01	.42
32 MAR 3	8.00	2.40	40.00	.000	.436	.009	4248.	.6597	.019	.023	1.4734	.01	.18

Degree-day thickness= .458

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	45.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.00	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	1.00	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

New porosity due to interblock freezing = 1.000

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	45.00	.000	.012	.007	4214.	.6544	.000	.000	1.4656	.01	-.12
2 FEB 1	-.80	1.00	45.00	.000	.024	.004	4531.	.7039	.000	.000	1.5387	.01	-.27
3 FEB 2	-3.20	2.00	45.00	.000	.039	.002	4720.	.7334	.000	.000	1.5823	.01	-.52
4 FEB 3	-.60	2.20	45.00	.000	.051	.002	4725.	.7342	.000	.000	1.5835	.01	-.54
5 FEB 4	-4.00	1.20	45.00	.000	.065	.001	4821.	.7491	.001	.001	1.6055	.01	-.82
6 FEB 5	-5.90	6.10	45.00	.000	.087	.001	4946.	.7686	.001	.001	1.6345	.01	-1.69
7 FEB 6	-10.50	3.00	45.00	.000	.110	.000	4986.	.7749	.002	.002	1.6437	.01	-2.29
8 FEB 7	-8.40	2.50	45.00	.000	.129	.000	4978.	.7737	.002	.002	1.6419	.01	-2.16
9 FEB 8	-10.90	1.80	45.00	.000	.147	.000	4996.	.7765	.003	.003	1.6460	.01	-2.50
10 FEB 9	-9.30	2.50	45.00	.000	.165	.000	5006.	.7779	.004	.004	1.6482	.01	-2.72
11 FEB 10	-12.20	1.90	45.00	.000	.184	.000	5022.	.7805	.005	.005	1.6520	.01	-3.18
12 FEB 11	-9.20	1.50	45.00	.000	.200	.000	5009.	.7785	.006	.006	1.6490	.01	-2.81
13 FEB 12	-10.90	3.20	45.00	.000	.218	.000	5038.	.7830	.007	.007	1.6557	.01	-3.74
14 FEB 13	-16.30	2.90	45.00	.000	.239	.000	5063.	.7869	.008	.008	1.6615	.01	-5.05
15 FEB 14	-11.40	2.80	45.00	.000	.258	.000	5047.	.7844	.009	.010	1.6577	.01	-4.13
16 FEB 15	-13.50	3.70	45.00	.000	.276	.000	5063.	.7869	.011	.011	1.6614	.01	-5.03
17 FEB 16	-28.00	3.60	45.00	.000	.303	.000	5102.	.7931	.013	.013	1.6706	.01	-9.19
18 FEB 17	-28.20	2.40	45.00	.000	.332	.000	5099.	.7925	.016	.016	1.6697	.01	-8.58
19 FEB 18	-32.70	1.50	45.00	.000	.357	.000	5099.	.7925	.018	.018	1.6697	.01	-8.60
20 FEB 19	-34.20	2.00	45.00	.000	.382	.000	5108.	.7939	.021	.021	1.6718	.01	-10.16
21 FEB 20	-20.30	2.50	45.00	.000	.408	.000	5091.	.7913	.024	.024	1.6679	.01	-7.52
22 FEB 21	-19.50	3.60	45.00	.000	.427	.000	5094.	.7917	.026	.026	1.6686	.01	-7.91
23 FEB 22	-12.00	1.80	45.00	.000	.446	.000	5069.	.7879	.028	.029	1.6628	.01	-5.45
24 FEB 23	-2.50	2.30	45.00	.000	.459	.000	5016.	.7796	.029	.030	1.6507	.01	-3.01
25 FEB 24	3.20	2.80	45.00	.000	.467	.001	4885.	.7591	.029	.030	1.6203	.01	-1.15
26 FEB 25	11.30	7.10	45.00	.000	.472	.000	5026.	.7812	.031	.032	1.6529	.01	3.37
27 FEB 26	9.20	4.00	45.00	.000	.463	.001	4916.	.7640	.029	.030	1.6276	.01	1.44
28 FEB 27	6.50	1.70	45.00	.000	.459	.001	4892.	.7601	.028	.029	1.6219	.01	-1.19
29 FEB 28	12.20	3.80	45.00	.000	.463	.000	4985.	.7747	.030	.030	1.6434	.01	2.33
30 MAR 1	8.00	3.00	45.00	.000	.456	.003	4632.	.7196	.025	.028	1.5619	.01	.43
31 MAR 2	9.20	2.30	45.00	.000	.455	.011	4175.	.6483	.020	.024	1.4566	.01	.17
32 MAR 3	8.00	2.40	45.00	.000	.455	.012	3883.	.6026	.020	.023	1.3891	.01	-.06

Degree-day thickness= .456

APPENDIX B

INPUT & OUPUT FOR PROGRAM "ICE GROW"

- VARIATION OF POROSITY AND SAIL HEIGHT RUNS FOR REFREEZING OF ICE RUBBLE IN TEST BASIN

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	40.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.25	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	.20	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

Transient time: 14.42 hrs, ice growth= .001 m
New porosity due to interblock freezing = .192

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	40.00	.000	.015	.010	4043.	.6276	.000	.000	1.4260	.01	-.09
2 FEB 1	-.80	1.00	40.00	.000	.050	.003	4597.	.7141	.000	.000	1.5539	.01	-.13
3 FEB 2	-3.20	2.00	40.00	.000	.085	.002	4735.	.7357	.001	.001	1.5857	.01	-.56
4 FEB 3	-.60	2.20	40.00	.000	.116	.002	4730.	.7350	.002	.002	1.5847	.01	-.55
5 FEB 4	-4.00	1.20	40.00	.000	.144	.001	4872.	.7572	.003	.003	1.6175	.01	-1.07
6 FEB 5	-5.90	6.10	40.00	.000	.182	.001	4886.	.7593	.004	.005	1.6207	.01	-1.76
7 FEB 6	-10.50	3.00	40.00	.000	.214	.001	4971.	.7726	.006	.006	1.6402	.01	-2.34
8 FEB 7	-8.40	2.50	40.00	.000	.260	.001	4974.	.7730	.009	.010	1.6409	.01	-2.05
9 FEB 8	-10.50	1.80	40.00	.000	.296	.000	5005.	.7778	.012	.012	1.6480	.01	-2.70
10 FEB 9	-9.30	2.50	40.00	.000	.342	.000	5004.	.7777	.015	.015	1.6479	.01	-2.66
11 FEB 10	-12.20	1.90	40.00	.000	.373	.000	5026.	.7815	.019	.020	1.6535	.01	-3.39
12 FEB 11	-9.20	1.50	40.00	.000	.420	.000	5024.	.7808	.024	.025	1.6525	.01	-3.05
13 FEB 12	-10.90	3.20	40.00	.000	.455	.000	5031.	.7820	.029	.029	1.6541	.01	-3.49
14 FEB 13	-16.30	2.90	40.00	.000	.473	.000	5059.	.7862	.031	.032	1.6604	.01	-4.78
15 FEB 14	-11.40	2.80	40.00	.000	.535	.000	5044.	.7839	.040	.041	1.6570	.01	-3.99
16 FEB 15	-13.50	3.70	40.00	.000	.561	.000	5054.	.7856	.044	.045	1.6595	.01	-4.52
17 FEB 16	-28.00	3.60	40.00	.000	.538	.000	5094.	.7918	.041	.042	1.6687	.01	-7.98
18 FEB 17	-28.20	2.40	40.00	.000	.598	.000	5096.	.7921	.051	.052	1.6691	.01	-8.21
19 FEB 18	-32.70	1.50	40.00	.000	.640	.000	5102.	.7930	.059	.059	1.6705	.01	-9.12
20 FEB 19	-34.20	2.00	40.00	.000	.682	.000	5108.	.7939	.066	.067	1.6717	.01	-10.13
21 FEB 20	-20.30	2.50	40.00	.000	.808	.000	5090.	.7911	.093	.094	1.6677	.01	-7.42
22 FEB 21	-19.50	3.60	40.00	.000	.853	.000	5089.	.7910	.104	.105	1.6675	.01	-7.30
23 FEB 22	-12.00	1.80	40.00	.000	.937	.000	5073.	.7885	.125	.127	1.6639	.01	-5.79
24 FEB 23	-2.50	2.30	40.00	.000	1.064	.000	5016.	.7796	.158	.162	1.6507	.01	-3.01
25 FEB 24	3.20	2.80	40.00	.000	1.164	.001	4848.	.7533	.180	.188	1.6118	.01	-.94
26 FEB 25	11.30	7.10	40.00	.000	1.387	.000	5027.	.7813	.270	.278	1.6531	.01	3.09
27 FEB 26	9.20	4.00	40.00	.000	1.279	.001	4945.	.7685	.223	.231	1.6342	.01	1.72
28 FEB 27	6.50	1.70	40.00	.000	1.138	.001	4869.	.7566	.173	.180	1.6167	.01	-1.05
29 FEB 28	12.20	3.80	40.00	.000	1.326	.000	5003.	.7776	.245	.251	1.6477	.01	2.11
30 MAR 1	8.00	3.00	40.00	.000	1.211	.002	4786.	.7437	.189	.201	1.5976	.01	.78
31 MAR 2	9.20	2.30	40.00	.000	1.197	.002	4694.	.7293	.179	.192	1.5762	.01	.53
32 MAR 3	8.00	2.40	40.00	.000	1.181	.006	4397.	.6830	.152	.174	1.5078	.01	.24

Degree-day thickness= 1.049

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	40.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.25	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	.25	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

Transient time: 14.58 hrs, ice growth= .001 m
New porosity due to interblock freezing = .242

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	40.00	.000	.012	.011	3533.	.6104	.000	.000	1.4006	.0	-.07
2 FEB 1	-.80	1.00	40.00	.000	.040	.004	4525.	.7029	.000	.000	1.5373	.01	-.27
3 FEB 2	-3.20	2.00	40.00	.000	.068	.002	4676.	.7265	.001	.001	1.5722	.01	-.44
4 FEB 3	-.60	2.20	40.00	.000	.092	.002	4671.	.7257	.001	.001	1.5711	.01	-.43
5 FEB 4	-4.00	1.20	40.00	.000	.117	.001	4832.	.7509	.002	.002	1.6092	.0	-.61
6 FEB 5	-5.90	6.10	40.00	.000	.147	.001	4850.	.7536	.003	.003	1.6123	.01	-.82
7 FEB 6	-10.50	3.00	40.00	.000	.176	.001	4947.	.7688	.004	.004	1.6347	.0	-1.01
8 FEB 7	-8.40	2.50	40.00	.000	.214	.001	4951.	.7694	.006	.006	1.6356	.0	-1.21
9 FEB 8	-10.90	1.80	40.00	.000	.246	.000	4986.	.7749	.008	.009	1.6437	.0	-1.71
10 FEB 9	-9.30	2.50	40.00	.000	.284	.000	4986.	.7750	.011	.011	1.6438	.0	-2.0
11 FEB 10	-12.20	1.90	40.00	.000	.313	.000	5014.	.7792	.014	.014	1.6501	.0	-2.31
12 FEB 11	-9.20	1.50	40.00	.000	.351	.000	5009.	.7785	.017	.018	1.6490	.0	-2.6
13 FEB 12	-10.90	3.20	40.00	.000	.382	.000	5018.	.7800	.020	.021	1.6512	.0	-2.9
14 FEB 13	-16.30	2.90	40.00	.000	.403	.000	5049.	.7847	.023	.023	1.6582	.0	-3.1
15 FEB 14	-11.40	2.80	40.00	.000	.452	.000	5033.	.7822	.029	.029	1.6545	.0	-4.2
16 FEB 15	-13.50	3.70	40.00	.000	.477	.000	5045.	.7842	.032	.033	1.6574	.01	-4.8
17 FEB 16	-28.00	3.60	40.00	.000	.472	.000	5089.	.7910	.032	.032	1.6674	.0	-4.8
18 FEB 17	-28.20	2.40	40.00	.000	.525	.000	5091.	.7912	.039	.040	1.6678	.0	-5.2
19 FEB 18	-32.70	1.50	40.00	.000	.566	.000	5097.	.7922	.046	.046	1.6693	.0	-5.5
20 FEB 19	-34.20	2.00	40.00	.000	.605	.000	5103.	.7932	.052	.053	1.6707	.0	-6.2
21 FEB 20	-20.30	2.50	40.00	.000	.703	.000	5085.	.7903	.070	.071	1.6665	.0	-8.0
22 FEB 21	-19.50	3.60	40.00	.000	.741	.000	5084.	.7902	.078	.079	1.6663	.0	-8.6
23 FEB 22	-12.00	1.80	40.00	.000	.807	.000	5067.	.7876	.092	.094	1.6624	.0	-8.7
24 FEB 23	-2.50	2.30	40.00	.000	.895	.000	5007.	.7782	.111	.114	1.6485	.0	-8.5
25 FEB 24	3.20	2.80	40.00	.000	.960	.001	4828.	.7502	.121	.127	1.6073	.0	-2.7
26 FEB 25	11.30	7.10	40.00	.000	1.092	.000	5019.	.7801	.167	.171	1.6514	.0	-.8
27 FEB 26	9.20	4.00	40.00	.000	1.024	.001	4933.	.7667	.143	.148	1.6315	.01	3.1
28 FEB 27	6.50	1.70	40.00	.000	.939	.001	4848.	.7534	.117	.122	1.6119	.01	1.8
29 FEB 28	12.20	3.80	40.00	.000	1.049	.000	4994.	.7761	.153	.157	1.6455	.01	-.9
30 MAR 1	8.00	3.00	40.00	.000	.979	.002	4767.	.7407	.123	.130	1.5932	.01	2.8
31 MAR 2	9.20	2.30	40.00	.000	.969	.003	4669.	.7254	.116	.125	1.5706	.01	.8
32 MAR 3	8.00	2.40	40.00	.000	.959	.007	4359.	.6769	.098	.113	1.4989	.01	.22

Degree-day thickness= .933

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	40.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.25	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	.30	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

Transient time: 14.74 hrs, ice growth= .000 m
New porosity due to interblock freezing = .293

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	40.00	.000	.010	.013	3843.	.5984	.000	.000	1.3806	.01	-.71
2 FEB 1	-.80	1.00	40.00	.000	.033	.004	4458.	.6825	.000	.000	1.5219	.01	-.73
3 FEB 2	-3.20	2.00	40.00	.000	.056	.003	4626.	.7177	.000	.000	1.5582	.01	-.84
4 FEB 3	-.60	2.20	40.00	.000	.076	.003	4613.	.7167	.001	.001	1.5577	.01	-.82
5 FEB 4	-4.00	1.20	40.00	.000	.097	.001	4793.	.7448	.001	.001	1.5891	.01	-.77
6 FEB 5	-5.90	6.10	40.00	.000	.122	.001	4812.	.7477	.002	.002	1.6035	.01	-.7
7 FEB 6	-10.50	3.00	40.00	.000	.148	.001	4921.	.7648	.003	.003	1.6288	.01	-1.4
8 FEB 7	-8.40	2.50	40.00	.000	.180	.001	4927.	.7657	.004	.005	1.6300	.01	-1.61
9 FEB 8	-10.90	1.80	40.00	.000	.208	.001	4966.	.7718	.006	.006	1.6391	.01	-1.91
10 FEB 9	-9.30	2.50	40.00	.000	.240	.001	4968.	.7720	.008	.008	1.6394	.01	-1.77
11 FEB 10	-12.20	1.90	40.00	.000	.267	.000	4958.	.7768	.010	.010	1.6465	.01	-2.15
12 FEB 11	-9.20	1.50	40.00	.000	.300	.000	4993.	.7760	.012	.013	1.6454	.01	-2.41
13 FEB 12	-10.90	3.20	40.00	.000	.326	.000	5005.	.7778	.015	.015	1.6480	.01	-2.67
14 FEB 13	-16.30	2.90	40.00	.000	.348	.000	5038.	.7831	.017	.017	1.6558	.01	-3.75
15 FEB 14	-11.40	2.80	40.00	.000	.389	.000	5021.	.7804	.021	.021	1.6518	.01	-3.15
16 FEB 15	-13.50	3.70	40.00	.000	.412	.000	5035.	.7826	.024	.024	1.6551	.01	-3.54
17 FEB 16	-28.00	3.60	40.00	.000	.417	.000	5083.	.7900	.025	.025	1.6680	.01	-6.61
18 FEB 17	-28.20	2.40	40.00	.000	.485	.000	5085.	.7903	.031	.031	1.6685	.01	-6.71
19 FEB 18	-32.70	1.50	40.00	.000	.504	.000	5081.	.7914	.036	.037	1.6680	.01	-7.67
20 FEB 19	-34.20	2.00	40.00	.000	.541	.000	5099.	.7925	.042	.042	1.6697	.01	-8.01
21 FEB 20	-20.30	2.50	40.00	.000	.619	.000	5079.	.7894	.054	.055	1.6652	.01	-4.28
22 FEB 21	-19.50	3.60	40.00	.000	.652	.000	5079.	.7894	.060	.061	1.6651	.01	-6.11
23 FEB 22	-12.00	1.80	40.00	.000	.705	.000	5060.	.7865	.070	.071	1.6608	.01	-4.27
24 FEB 23	-2.50	2.30	40.00	.000	.769	.000	4997.	.7766	.082	.084	1.6462	.01	-2.51
25 FEB 24	3.20	2.80	40.00	.000	.815	.001	4807.	.7470	.087	.091	1.6024	.01	-.77
26 FEB 25	11.30	7.10	40.00	.000	.898	.000	5011.	.7789	.113	.115	1.6496	.01	2.53
27 FEB 26	9.20	4.00	40.00	.000	.852	.001	4921.	.7647	.098	.102	1.6286	.01	1.48
28 FEB 27	6.50	1.70	40.00	.000	.796	.001	4827.	.7501	.083	.087	1.6070	.01	-.71
29 FEB 28	12.20	3.80	40.00	.000	.868	.000	4984.	.7745	.104	.107	1.6431	.01	2.01
30 MAR 1	8.00	3.00	40.00	.000	.819	.002	4747.	.7376	.085	.091	1.5886	.01	.53
31 MAR 2	9.20	2.30	40.00	.000	.811	.003	4644.	.7215	.081	.087	1.5647	.01	.45
32 MAR 3	8.00	2.40	40.00	.000	.804	.007	4318.	.6705	.068	.079	1.4895	.01	.21

Degree-day thickness= .849

ICE GROWTH MODEL WITH SHIP TRACK
Version 1.00

RUN 0 RUBBLE

INPUT PARAMETERS AND OPTIONS:

Long wave radiation	40.00	W/m**2
Snow cover	.00	m
Initial ice thickness	.001	m
Initial sail thickness	.20	m
Initial keel thickness	10.00	m
Temperature of water	-.01	oC
Freezing temperature of water	-.01	oC
Average initial rubble temperature	-1.00	oC
Initial rubble porosity	.25	
Initial salinity of sail	10.00	ppt
Heat transfer coefficient of ice	.00175	
Heat transfer coefficient of sail	.00175	
Heat transfer coefficient of snow	.00175	
Specific heat of snow	.42	KJ/KgoC
Thermal conductivity of snow	.21	W/moC
Degree day method coefficient	.90	
Coefficient "A"	5230.00	
Coefficient "B"	-13000.00	
Coefficient "C"	.81	
Coefficient "D"	-2.03	
Coefficient "E"	1.70	
Coefficient "F"	-3.00	
Coefficient "M"	.50	
Coefficient "N"	.50	
Coefficient "O"	.50	
Starting day	JAN 31	
Ending day	MAR 3	
Total number of days	32	
Air temperature method	DAILY	
Wind velocity method	DAILY	
Long wave radiation method	CONSTANT	
Snow cover method	CONSTANT	
Allow negative sensible heat, ice growth.	YES	
Surface temperature allowed to be < Ta	YES	
Salinity method	GRADIENT	
Salinity at top of ice sheet	.01	ppt
Salinity at bottom of ice sheet	.01	ppt

Transient time: 8.96 hrs, ice growth= .000 m
New porosity due to interblock freezing = .242

DAY	AIR TEMP. (oC)	WIND VELOCITY (m/sec)	LONG WAVE RADIATION (W/m**2)	SNOW COVER (m)	ICE THICKNESS (m)	BRINE VOLUME	ELASTIC MODULUS (MPa)	TENSILE STRENGTH (MPa)	MOMENT CAPACITY UP (MN)	MOMENT CAPACITY DOWN (MN)	CRUSHING STRENGTH (MPa)	AVERAGE SALINITY (ppt)	AVERAGE TEMP. (oC)
1 JAN 31	2.00	.90	40.00	.000	.019	.007	4212.	.6541	.000	.000	1.4651	.01	-.10
2 FEB 1	-.80	1.00	40.00	.000	.049	.003	4609.	.7160	.000	.000	1.5567	.01	-.35
3 FEB 2	-3.20	2.00	40.00	.000	.080	.002	4735.	.7357	.001	.001	1.5858	.01	-.53
4 FEB 3	-.60	2.20	40.00	.000	.105	.002	4724.	.7340	.001	.001	1.5832	.01	-.59
5 FEB 4	-4.00	1.20	40.00	.000	.132	.001	4866.	.7562	.002	.002	1.6160	.01	-1.04
6 FEB 5	-5.90	6.10	40.00	.000	.164	.001	4887.	.7595	.004	.004	1.6209	.01	-1.17
7 FEB 6	-10.50	3.00	40.00	.000	.198	.001	4971.	.7726	.005	.005	1.6403	.01	-2.04
8 FEB 7	-8.40	2.50	40.00	.000	.238	.001	4972.	.7728	.008	.008	1.6405	.01	-2.28
9 FEB 8	-10.90	1.80	40.00	.000	.272	.000	5003.	.7775	.010	.010	1.6475	.01	-2.83
10 FEB 9	-9.30	2.50	40.00	.000	.310	.000	5002.	.7774	.013	.014	1.6475	.01	-3.14
11 FEB 10	-12.20	1.90	40.00	.000	.347	.000	5027.	.7813	.016	.017	1.6531	.01	-3.69
12 FEB 11	-9.20	1.50	40.00	.000	.381	.000	5021.	.7804	.020	.021	1.6518	.01	-3.15
13 FEB 12	-10.90	3.20	40.00	.000	.412	.000	5030.	.7818	.024	.024	1.6539	.01	-3.46
14 FEB 13	-16.30	2.90	40.00	.000	.435	.000	5058.	.7862	.027	.027	1.6604	.01	-4.74
15 FEB 14	-11.40	2.80	40.00	.000	.485	.000	5043.	.7837	.033	.034	1.6568	.01	-3.94
16 FEB 15	-13.50	3.70	40.00	.000	.511	.000	5054.	.7855	.037	.037	1.6594	.01	-4.51
17 FEB 16	-28.90	3.60	40.00	.000	.508	.000	5095.	.7919	.037	.037	1.6689	.01	-8.08
18 FEB 17	-28.20	2.40	40.00	.000	.563	.000	5096.	.7921	.045	.046	1.6692	.01	-8.25
19 FEB 18	-32.70	1.50	40.00	.000	.605	.000	5102.	.7930	.052	.053	1.6705	.01	-9.09
20 FEB 19	-34.20	2.00	40.00	.000	.644	.000	5108.	.7939	.059	.060	1.6718	.01	-10.12
21 FEB 20	-20.30	2.50	40.00	.000	.742	.000	5090.	.7911	.079	.080	1.6676	.01	-7.37
22 FEB 21	-19.50	3.60	40.00	.000	.781	.000	5089.	.7910	.087	.088	1.6675	.01	-7.36
23 FEB 22	-12.00	1.80	40.00	.000	.848	.000	5072.	.7883	.102	.104	1.6635	.01	-5.86
24 FEB 23	-2.50	2.30	40.00	.000	.937	.000	5014.	.7793	.122	.125	1.6501	.01	-2.84
25 FEB 24	3.20	2.80	40.00	.000	1.004	.001	4843.	.7525	.133	.139	1.6106	.01	-.91
26 FEB 25	11.30	7.10	40.00	.000	1.138	.000	5025.	.7810	.182	.186	1.6526	.01	3.33
27 FEB 26	9.20	4.00	40.00	.000	1.069	.001	4941.	.7679	.156	.161	1.6333	.01	1.69
28 FEB 27	6.50	1.70	40.00	.000	.982	.001	4862.	.7555	.128	.134	1.6150	.01	-1.31
29 FEB 28	12.20	3.80	40.00	.000	1.095	.000	5000.	.7771	.167	.171	1.6469	.01	2.84
30 MAR 1	8.00	3.00	40.00	.000	1.023	.002	4779.	.7425	.135	.143	1.5959	.01	.78
31 MAR 2	9.20	2.30	40.00	.000	1.013	.002	4682.	.7275	.127	.137	1.5736	.01	.51
32 MAR 3	8.00	2.40	40.00	.000	1.003	.006	4378.	.6799	.109	.125	1.5034	.01	.23

Degree-day thickness= .932